THE RAINFALL OF THE BRITISH ISLES

M. DE CARLE S. SALTER

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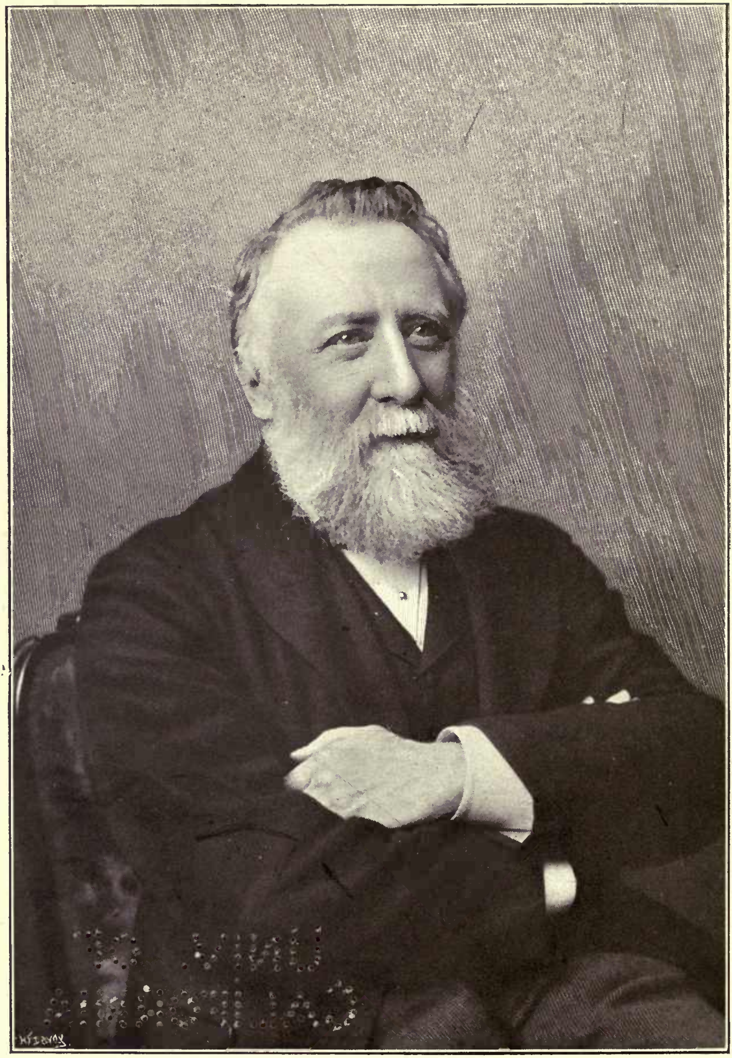

THE LATE GEORGE JAMES SYMONS, F.R.S.
FOUNDER OF THE BRITISH RAINFALL ORGANIZATION.

[*Frontispiece*

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BY

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" . . . like the phenomena of nature, like the sun and the sea, the stars and the flowers, like frost and snow, rain and dew, hailstorm and thunder, which are to be studied with entire submission of our own faculties, and in the perfect faith that in them there can be no too much or too little, nothing useless or inert, but that, the farther we press in our discoveries, the more we shall see proofs of design and self-supporting arrangement where the careless eye had seen nothing but accident!"—De Quincey, "*On the Knocking at the Gate in Macbeth.*"

LONDON

UNIVERSITY OF LONDON PRESS, LTD.

17 WARWICK SQUARE, E.C.4

1921

PREFACE

I have frequently been struck by the need for a book summarizing the results of many years of labour in compiling and studying statistics of the rainfall of the British Isles. A very large number of papers and articles on various aspects of the subject have been published from time to time, and it has been dealt with in a more or less cursory manner in many books on meteorology and physiography; but on being asked by engineers, teachers, and students for reference to any volume giving general information on the subject, I have constantly found myself at a loss.

In endeavouring to meet this need I am aware that I am drawing freely on the work of others, more especially of my predecessors in the direction of the British Rainfall Organization. I have tried in every instance to acknowledge this, but after twenty-four years of active participation in the work of the Organization, dating back to the lifetime of its founder and covering the administration of his successors, Mr. Sowerby Wallis and Dr. H. R. Mill, it is difficult always to know exactly how lines of research originated.

I am in an especial degree indebted to Dr. H. R. Mill for constant encouragement and teaching during the nineteen years when I had the privilege of working under him.

I have to acknowledge the permission of the

Institution of Water Engineers to reprint portions of my recent paper on "The Relation of Rainfall to Configuration," and to thank the Royal Meteorological Society for a similar courtesy in respect of my paper on "The Measurement of Rainfall Duration."

Acknowledgments are also due to the Director of the Meteorological Office, the Royal Meteorological Society, Messrs. Casella & Co., Messrs. Negretti & Zambra, and Mr. J. Baxendell for the loan of blocks and drawings. The remainder of the illustrations have been prepared by Mr. A. T. Bench.

Throughout this volume I have used the English inch as a unit of measurement of rainfall in preference to the millimetre, believing it to be more familiar to the majority of readers. I have endeavoured to avoid the use of unnecessary technical terms, and have assumed only an elementary acquaintance with physics and meteorology.

CARLE SALTER.

62, CAMDEN SQUARE,
LONDON, N.W.1.
July 1921.

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CHAPTER I

INTRODUCTORY

The study of the distribution of rainfall has commonly been regarded as a branch of Meteorology, or more particularly of Climatology, and most of the attention which has been given to the subject has therefore come from those who have made these sciences their special concern. In certain respects the classification is undoubtedly justified: precipitation of aqueous vapour from the atmosphere, in all its forms, is one of the central phenomena round which much of the science of meteorology revolves; and the seasonal and regional distributions of this all-important climatic element are among the main considerations of Climatology. It is of course impossible rigidly to delimit the spheres of Climatology and Geography, which have much that is common ground; but it should be noted that it is very largely by geographical methods that the most important additions to our knowledge of the natural control of rainfall distribution have been made. It is necessary to point out, however, that any empirical method of studying natural phenomena, however complete and systematic, is at best capable of yielding only a one-sided view of the subject as a whole, so that, in the present instance, the aid of experimental physics is an essential adjunct to direct

observations in attempting to arrive at an understanding of the natural laws which they illustrate.

The problem of atmospheric precipitation as it has presented itself to the student of pure meteorology, by itself as limited as that approached solely from the geographical side, is one of exceptional complexity. The atmosphere, the theatre of the operations which he is examining, is an enormous and almost unconfined mass of elastic fluid in a state of perpetual movement along complicated paths and in three dimensions. It is constantly varying in respect of its temperature, pressure, transparency, humidity, electrical condition, and probably also in other ways of which we are not even cognizant. These variables are intimately correlated by laws not always fully understood, in some cases not even known, and nearly all have an important bearing on the condensation of moisture from a gaseous to a liquid form which constitutes the phenomenon of precipitation. Owing to our position at the bottom of the ocean of air, and to the vast extent of that ocean, direct observation of the variations in the conditions enumerated is limited in its scope. Some of the factors can be more or less accurately measured in the portions of the atmosphere accessible by human or mechanical means; others can be observed only by rough-and-ready methods. As an example, the vital question of obtaining records of atmospheric humidity, by which its variations in space and time may be determined, has never been completely mastered; whilst the variations of temperature with which it is closely bound up are so great and so rapid that they can be followed only in the broadest outline. In applying mathematical reasoning to problems with so

many unknown, or only partially known, factors, it is necessary to introduce large assumptions and sometimes to ignore important side-issues in order to arrive at the required simplicity.

In spite of these difficulties, very considerable additions to our knowledge of the dynamics of the free atmosphere have resulted from research along geophysical lines, and the student who desires to approach the subject of rainfall distribution from the standpoint of the geographer will do well to acquaint himself as a preliminary with the work of the modern schools of meteorology. Among the more eminent of British meteorologists to whose writings attention may be drawn in this connection should be mentioned the late Dr. John Aitken, Mr. W. H. Dines, and Sir Napier Shaw, whose studies of the thermo-dynamics of the atmosphere have played a leading part in clearing away much of what was fundamentally wrong in the hypotheses of former schools of meteorology. Among foreign workers along similar lines perhaps the first place should be given to Professor V. F. Bjerknes, of Christiania, whose original methods of research into the complex dynamical reactions of the free atmosphere have been extremely illuminating.

In the more direct field of geographical research the student of rainfall problems, so far as these apply to the British Isles, is deeply indebted to the late Dr. Alexander Buchan, and in a still higher degree to the organizing ability and lifelong industry of the late George James Symons, who laid the foundation for the systematic observation of the rainfall in all parts of the country on a scale unparalleled in any part of the world, and in so doing

made possible the cartographical studies of Dr. H. R. Mill. It is from the very numerous maps of rainfall distribution constructed by Dr. Mill during the first twenty years of this century, and from his clear scientific deductions therefrom, that practically all our existing knowledge of the rainfall of the British Isles from the purely geographical side must be drawn. Work on similar lines in the north of Europe has been carried out with conspicuous success by Dr. G. Hellmann, of the German State Meteorological Service.

In referring to the co-ordinating work of the leaders of meteorological science it would not be just to omit reference to the large and devoted band of helpers in all parts of this country who, by the patient accumulation of data, achieved often only at considerable personal sacrifice, have been and still are constantly providing the raw material so essential to the progress of any observational research. Among the five thousand rainfall observers in the British Isles at the present day, there are, of course, a considerable number of paid officials, but by far the greater number are voluntary and self-equipped. Their individual interests are exceedingly diverse, and their willingness to work together on a uniform system, suggested from without, for the good of a common cause, implies not merely successful organization, but also a mutual bond of disinterested attachment to the science which they all unite to serve.

The great mass of statistical information bearing on the rainfall of the British Isles which has been brought together by the British Rainfall Organization, and is still being added to year by year, offers a rich field of material to any who care to delve in it. A good deal has, no doubt, been done, especially in

recent years, but that far more awaits the doing is certain. What lines future research may take it is impossible to say, and whether any purely mathematical treatment will yield generalizations of value remains still to be proved. The work so far attempted may be briefly summed up as a partial study of the subject from two broad points of view, the variations of amount of rainfall in Time and its variations in Space. In regard to the actual weather experienced day by day the variability in both these respects is very great, and without close study the fall of rain appears to be among the most capricious and unregulated of all natural phenomena. Meteorology has shown, however, that, in spite of its seeming waywardness, rainfall is controlled, like everything else in nature, by fixed and comprehensible laws; and that as we widen our purview the limits of variability in time and in space become narrower and narrower. Whether the period covered by trustworthy observations has as yet been long enough to enable us to fix the limits of variability with certainty is doubtful, but it appears to have been sufficient for us to obtain some insight into the operation of the main controlling factors.

The object of this book is to bring together some of the general conclusions so far deduced; to suggest, rather than formulate, a working hypothesis which future students of the subject may build upon or amend, and to draw attention to the economic utility of a more complete knowledge of our resources in respect of one of Nature's greatest gifts.

CHAPTER II

THE PHYSICAL PROCESSES OF RAIN FORMATION

It is principally in connexion with the physical and dynamical processes operating in the atmosphere that the student of the geographical aspects of rainfall must look to the physicist and mathematician for collaboration in order to gain that second viewpoint so essential in obtaining a clear conception of the natural laws underlying the phenomena which his observations illustrate.

It is difficult, in some cases impossible, to reproduce in a laboratory the precise conditions of nature, the more so when these conditions occur in a theatre so vast as the free atmosphere, and are complicated by factors which are in many cases unknown and inaccessible to direct observation. On this account there is still much to be learnt of the physical reactions which take part in the production of observed weather phenomena, but by a process of repeated simplification and constant readjustment of hypothetical reasoning to fit with observed facts certain invariable laws have been formulated which there is every reason to regard as representing the fundamental basis of rainfall formation. It is from work along these lines that the following brief summary of the physical processes of rainfall has been drawn.

All the varied phenomena of aqueous precipitation

from the atmosphere, of which rainfall is the most important, depend upon the fact that water, under certain conditions of temperature and pressure, is capable of existing in the form of vapour. Water-vapour obeys the same physical laws as any other gas, and if added to a fixed volume of dry air operates in increasing the pressure exerted by that air, i.e. its weight, in exactly the same way as if an equal quantity of any other gas were introduced. The limit to the capacity of water to remain in the form of vapour is determined entirely by temperature, and therefore the amount of water-vapour which can exist in a definite volume of air varies in accordance with the temperature of the air. The existence of air is not, of course, theoretically essential for the existence of water-vapour, but in natural conditions air is always present, and the above statement holds good. Air which is more or less dry will readily take up moisture from any available source by evaporation, and, provided sufficient water is available, evaporation will continue until a certain vapour-pressure is attained (varying with the temperature), after which no further evaporation will take place unless the temperature rises.

Temperature in degrees Fahr.	Percentage of normal[1] air-pressure.
32	0·6
50	1·2
78	3·2
96	5·9
114	8·3
211	100

[1] These values are adapted from Sir Napier Shaw's *Forecasting Weather*, p. 153.

The vapour-pressure attainable at certain specific temperatures may be expressed in percentages of normal atmospheric pressure, taken for convenience as 1,000 millibars, equivalent to 750 millimetres, or 29·5 inches of mercury on the ordinary barometer scale. The slight difference between the last temperature given (211°) and the boiling-point of water (212°) arises from the pressure being taken for the purpose of the calculation at 750 mm. instead of 760 mm. or 29·92 inches, which is about the mean value for sea-level.

Air which contains the largest possible quantity of water-vapour for its temperature is said to be saturated, and the temperature at which any body of air becomes saturated is known as the dew-point. Any additional quantity of water-vapour introduced could not remain in the gaseous form and, except under conditions which will be mentioned later, must necessarily condense. It follows further from this law that if air containing water-vapour be cooled to the temperature of its dew-point, it will *ipso facto* become saturated. Further cooling will bring about condensation of part of the water-vapour until equilibrium is re-established, partly by the lowering of the dew-point occasioned by the diminished quantity of water-vapour remaining, and partly by the release of heat in the process of condensation. Such condensation by cooling is the only means known in nature by which water is withdrawn from the atmosphere, and atmospheric cooling is therefore essential for all precipitation.

Before considering these temperature changes in detail it is convenient to draw attention to the conditions under which condensation of water-vapour takes place in the atmosphere. In order that

this may occur it has been shown to be necessary that some nucleus should exist upon which the condensed water-drop may form. If such is not present, cooling may proceed beyond the dew-point without condensation, the air passing beyond saturation to the abnormal condition known as super-saturation. Aitken has demonstrated this clearly under artificial conditions, but it is highly probable that such a phenomenon never occurs in nature.

In the case of atmospheric cooling brought about by conduction of heat from the air to any solid body such as the earth, a building, or plant, this body itself forms the required nucleus, and when cooling has proceeded to the stage of condensation, dew or hoar-frost is deposited. In the free air the nucleus is readily provided by dust-particles and other minutely subdivided matter held in suspension. Aitken's investigations of the dust-content of the air have shown that at all elevations within the reach of water-vapour sufficient dust exists to provide the necessary nuclei,[1] and the conditions of condensation in the absence of dust, although of great scientific interest, are not immediately applicable. It is, however, noteworthy that even in the complete absence of solid nuclei condensation will take place, after a high degree of super-saturation has been attained, on the electrified ions produced by the dissociation of atoms, as has been proved by Mr. C. T. R. Wilson.

The first stages of normal condensation in the free atmosphere may be pictured as the coating with moisture of the floating dust-particles. These particles themselves, at any rate in the upper atmo-

[1] *Proc. R. Soc. Edin.*, xvii, 1891, pp. 193–254.

sphere, are extremely minute,[1] but in spite of this an optical effect readily perceptible to the naked eye is produced. When dry, dust-particles reflect the light which falls on them, and do not, except by diffusion of light, interfere with the transparency of the air; when damp, they absorb a large proportion of this light, and if condensation brings this about, the air immediately becomes opaque. An example of this phenomenon is provided when steam is ejected into the air. On first issuing from the funnel of an engine steam is invisible, but directly it mixes with the cooler air, condensation takes place and a cloud is formed. It is a common error to speak of seeing a cloud of steam; as a matter of fact, the cloud is composed of liquid water deposited on the dust in the air, and when after a short exposure the droplets re-evaporate and return to the form of water-vapour, they again become invisible.

When natural condensation in the air occurs in contact with the earth, the phenomenon is commonly referred to as a mist, when in the upper air as a cloud. The two are similar in all respects, except that there may be a difference in the cause of the cooling which has given rise to the change from water-vapour to liquid form. True fog differs from mist in some respects which are not of importance in this connexion.

It is important at this point to observe that dust-particles, as has been pointed out by Aitken, have to a certain extent hygroscopic properties, so that when present in sufficient numbers they will induce

[1] As an example of the minuteness of dust-particles, Aitken computed that a single puff of cigarette smoke consisted of about 4,000,000,000 particles.

condensation even though the air is not completely saturated with moisture. This explains the persistence under certain conditions of haze or fog in comparatively dry air. Rain is, however, never formed in this way.

In the upper atmosphere the conditions under which clouds are formed are numerous, and the cloud may appear in a great variety of forms, some of which are extremely beautiful. It is foreign to the subject now under discussion to consider these varieties of cloud in detail, but it is of interest to notice the three important types classified by Luke Howard—the *Stratus*, or sheet-cloud, analogous to a high fog, the *Cumulus*, or heap-cloud, and the *Cirrus*, or hair-cloud. The two former are composed of water-droplets formed in the manner just described, and the Cirrus of ice-particles. The Cirrus is the most lofty of all clouds and is known to consist of ice on account of the peculiar optical effects which it produces.

When condensation, after reaching the cloud stage, is continued, the tiny water-particles of which the cloud is built up begin to coalesce, and as they become heavy enough to overcome the friction of the air, fall downwards by gravity. In all probability many of these drops are re-evaporated during their passage earthward, but those which escape are further augmented by collision with others and grow large enough to reach the earth as rain-drops. There is a limit to the size of rain-drops, since, owing to their velocity of descent, drops exceeding certain dimensions must be broken up again before reaching the ground.

It is not fully understood under exactly what conditions condensation in the atmosphere has the

effect of forming ice-crystals instead of liquid droplets. It is highly probable that the latter are frequently formed, even though the temperature is below the freezing-point of water under ordinary circumstances. It is, however, not improbable that a good deal of our ordinary rain is in the form of ice in its earliest stages and melts during its descent. If this melting is incomplete, the phenomenon of sleet is observed ; and if melting does not take place, the ice-crystals will reach the ground in the form of snow. In very cold climates individual ice-crystals or very small conglomerations fall, but in more temperate conditions masses of entangled and half-melted crystals form snow-flakes. Apart from the difference of temperature in the strata at which condensation occurs, there is not known to be any physical distinction between the conditions under which rain and snow are formed, so that for purposes of study the two may be regarded as merely different manifestations of the same phenomenon. The peculiar conditions giving rise to the formation of hail stones will be more conveniently dealt with later.

The conception of the fact that precipitation takes place in consequence of condensation on solid nuclei floating in the free air gives rise to speculation as to the origin of the occasional phenomena known as "black rain," "blood-rain," "milk-rain," etc., viz. rain bringing with it an admixture of foreign suspended matter, sufficient to cause discoloration. It appears probable, however, that the presence of such foreign matter may be due less to its having formed the actual nuclei for condensation than to the accident of its presence in the air lying between the condensation stratum and the earth. Such

impurities may consist of soot, plant-pollen, finely divided sulphur from manufacturing processes, sand, or numerous similar substances. The remarkable so-called "blood-rain" which occurred in the south of England and in Germany in February 1903 was shown to have been impregnated with mineral substances carried by air-drifts from the Saharan Desert.[1] The fine dust discharged in volcanic eruptions has been known to remain in suspension in the air for several years.

Under normal conditions rain is also found to contain a certain amount of salt and other soluble impurities. Observations by Angus Smith[2] and others show that the quantity present is much greater near the sea than inland, justifying the assumption that evaporated sea-spray is the source, but the products of manufactories also contribute a portion. The salt-content of the atmosphere is much greater in winter than in summer. Observations covering ten years at Rothamsted, Herts., gave an average deposit of about 26 lb. per acre per year.[3]

Instances are occasionally met with in which much more remarkable "impurities" are deposited in showers of rains. Among these may be mentioned recorded instances of showers of thousands of tiny fishes, of immature frogs and other small animals. There is no doubt that such phenomena are due to strong ascending air-currents, such as local whirlwinds, carrying these light objects away from the ground and transporting them through the

[1] See *Q.J.R. Met. Soc.*, vol. xxx, 1904, p. 57.

[2] See R. Angus Smith, *Air and Rain*, 1872.

[3] See *Journal of R. Agric. Soc. of England*, October 1883; and *Journal of Agric. Sci., London*, October 1919, vol. ix, pp. 309-37.

atmosphere until the force of gravity once more brings them to the earth.[1]

Apart from such abnormal cases there is no doubt that rain performs an important function in cleansing the air of impurities and bringing them to the ground both in suspended and dissolved form. The precipitation of ammonia and other nitrogenous matter with rain has an important bearing on its capacity to fertilize the soil. Valuable researches on the quantity and nature of atmospheric pollution are being carried out by the Committee on Atmospheric Pollution, under the superintendence of Dr. J. S. Owens for the Meteorological Office.[2]

When we look for the natural conditions under which the temperature of large masses of free air may be modified in such a manner as to give rise to changes in its vapour-content, these are found to be of several kinds. The variations in the amount of heat received from the sun might at first sight appear to be a potent factor in the situation, but we know that the transmission of solar heat to or from the atmosphere is for the most part indirect. The greater part of the sun's rays which reach the earth pass through the air without raising its temperature appreciably, and react on the land and sea. Part of the heat thus received is again lost by radiation through the air, but part is transmitted to the lower strata of the atmosphere by conduction. Similarly, when the

[1] An interesting account of a large number of phenomena of this nature, brought together by W. L. McAtee, of the U.S. Bureau of Biological Survey, is published in the *Monthly Weather Review* of the U.S.A. Department of Agriculture, vol. xlv (No. 5), May 1917, p. 217.

[2] An account of the work of the Committee on Atmospheric Pollution is given in a lecture by Dr. Owens, published in the *Q.J.R. Met. Soc.*, vol. xliv, 1918, p. 149.

surface of the earth is cooled below that of the air by radiation of heat into space, the layers of air in immediate contact are cooled by conduction. Although the atmosphere as a whole contains an almost inconceivably vast quantity of water in the form of vapour, the amount present in the shallow surface layer cooled by conduction is relatively insignificant. In addition to this, the conditions favourable for cooling by this process are those of relative calm, so that when slight condensation has reduced the available moisture supply, it is not renewed by the advent of fresh moist air.

Condensation of this kind commonly takes the form of dew or hoar-frost, or, under certain conditions, of mist or fog, and the total amount of water accruing to streams from this source, in temperate climates at any rate, is so small as to be negligible in comparison with true rainfall.

Other processes of cooling have been adduced to account for condensation of rain, among the most important of which is the supposed mixing of cold air with warm moist air. It can be shown that, although neither mass of air is in itself in a condition to condense its water-vapour, the mixture may have a temperature below the combined dew-point. As a matter of fact, air currents of different temperatures do not mix readily in nature, and if they do by any chance do so, as, for example, when churned together by eddy-motion, the amount of water released is quite small and seldom forms more than a cloud or fog-bank. It is probable, though not certain, that the admixture of air at different temperatures may take place at the planes of contact of superimposed strata, probably arising from eddy-motion induced by friction. In these circum-

stances incipient condensation, giving rise to more or less permanent cloud-layers, but not sufficiently pronounced to cause actual rain, may occur. The subject awaits fuller investigation.

Besides the temperature variations brought about in the atmosphere by insolation and conduction, which, as has been seen, are not sufficiently pronounced to account for the phenomenon of rain, an extremely important effect is produced by thermodynamic reaction. This process, which in nature probably seldom occurs entirely free from complication arising from the factors previously mentioned, is most easily studied if considered apart from them.

It is an accepted physical law that heat and work are different manifestations of energy, and in accordance with the law of the conservation of energy they are mutually convertible. If a thermally insulated body of air is compressed by any agency, some of the work expended in compressing it is converted into heat and the air is warmed. Inversely, if air under similar circumstances is released from pressure, being a gas it expands and is cooled. Changes of temperature arising in this way are known as adiabatic, since they occur without transference of heat from any adjacent body or mass of air.

The importance of adiabatic temperature changes in meteorology arises from the well-known fact that the density of the air varies in accordance with the pressure of the superincumbent strata, so that samples taken at different elevations above the earth's surface would show a decreasing density with increasing height.

During recent years the attention of meteorologists has been turned very largely to the study of the upper layers of the atmosphere, and a great mass

of observational data is now available bearing on the vertical temperature gradient, or "lapse-rate," under various conditions. Mr. W. H. Dines has calculated the mean temperature at various altitudes over England for each month of the year.[1]

Mean Monthly Temperature at various Altitudes for England in Degrees Fahrenheit

Height in Kilometres.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Height in miles.
14	− 71	− 69	− 64	− 61	− 60	− 58	− 60	− 61	− 64	− 69	− 71	− 72	8·7
13	− 71	− 69	− 64	− 61	− 60	− 58	− 58	− 61	− 64	− 66	− 69	− 71	8·1
12	− 69	− 66	− 64	− 63	− 61	− 60	− 60	− 61	− 61	− 64	− 66	− 69	7·5
11	− 69	− 69	− 69	− 64	− 63	− 61	− 60	− 60	− 61	− 63	− 64	− 66	6·8
10	− 63	− 63	− 63	− 60	− 56	− 54	− 52	− 52	− 52	− 56	− 58	− 61	6·2
9	− 56	− 54	− 56	− 52	− 47	− 44	− 37	− 40	− 40	− 44	− 48	− 54	5·6
8	− 45	− 47	− 45	− 42	− 35	− 31	− 26	− 26	− 26	− 31	− 35	− 42	5·0
7	− 33	− 35	− 33	− 29	− 24	− 18	− 15	− 13	− 15	− 18	− 26	− 31	4 3
6	− 22	− 22	− 20	− 17	− 11	− 6	0	0	− 2	− 8	− 11	− 18	3·7
5	− 9	− 11	− 9	-- 6	+ 1	+ 7	+ 10	+ 12	+ 10	+ 5	0	− 6	3·1
4	+ 3	+ 1	+ 3	+ 7	12	18	21	23	21	16	+ 10	+ 5	2·5
3	14	12	14	18	23	28	32	34	32	27	21	16	1·9
2	21	19	21	27	32	37	41	43	41	36	30	25	1·2
1	28	28	32	37	43	48	50	50	46	43	36	30	0·6
0	37	37	39	48	54	59	61	61	55	50	45	39	0

It will be observed by the above table that the temperature normally decreases by approximately 10° F. per kilometre, equivalent to about 1° F. per 300 feet, or 17° F. per mile of altitude up to about 11 kilometres, or 7 miles, beyond which it remains nearly stationary. The altitude at which temperature ceases to fall is variable, but it is always considerably beyond the limit of appreciable water condensation, so that it is not of direct importance in this connexion. The cause of the great and

[1] "On the Vertical Temperature Distribution of the Atmosphere over England," by W. H. Dines, F.R.S., *Phil. Trans.* Royal Society, Series A, vol. ccxi, pp. 255–78.

persistent lowering of temperature in the upper layers of the atmosphere is to be found entirely in the pressure conditions. Air which has descended to the lowest atmospheric strata, that is, near the surface of the earth, is compressed by the weight of the superincumbent air, which is about 15 lb. per square inch at sea-level, and the formation of heat in the process ensures the temperature being relatively high. As air ascends, the diminishing atmospheric pressure is associated with a diminishing atmospheric density, and in obedience to the thermo-dynamic law the temperature is correspondingly lower. The temperatures quoted in the above table are smoothed mean values and represent the probable normal vertical lapse-rate as observed by records obtained from kites and balloons. Although the temperature lapse-rate seldom differs largely from the normal, in certain types of weather wide variations are observed, amounting occasionally to inversion.

It should be observed that the mere fact of lower temperature at high levels is not in itself sufficient to account for precipitation, because in a quiescent atmosphere the amount of moisture present rapidly adjusts itself to any thermal conditions. Persistent condensation, such as that necessary to produce rain, only occurs, therefore, when moist air is ascending from the lower levels of the atmosphere to the upper, carrying with it the water-vapour proper to its original temperature, and at the same time being steadily cooled by expansion as it is released from pressure. In other words, it is not merely the fact of air being at a great height which conduces to its parting with its moisture in the form of rain, but the fact of its having *ascended* to that height from the lower strata. If, therefore, we wish to look for

the causes of rainfall it is necessary to examine the conditions under which air is caused to ascend. In forming the conception of vertical air-currents, which, it will be seen, play an extremely important part in determining weather conditions, it must not be assumed that the motion is necessarily directly upwards. In some circumstances, especially with intense rains, approximation to verticality may occur, but under ordinary conditions the phenomenon must be rather one of mounting a gradual incline.

So far as modern research goes, ascending air-currents sufficiently powerful to cause rain appear to occur in several entirely different sets of circumstances. These may be grouped in three classes: (i) Convectional, (ii) Cyclonic, and(iii) Orographical.

It is important to notice the characteristic features of these three types. Convectional rainfall is caused by the heating of part of the surface layer of the atmosphere, which expands and is forced to rise by the descent of the denser cool air around it. The fact that this air is warm usually results in its being charged with moisture which it will have taken up from the ground, from vegetation, or from any other available source. When the process of expansion under diminishing pressure has reduced the temperature of the rising mass to its dew-point, any further cooling will result in condensation. The heat set free in this process will to some extent check the cooling, but until stable equilibrium is re-established condensation must continue. The conditions described are probably fairly typical of what occurs in the common heat-thunderstorm of summer.

The intensity of rain observed in the most severe thunderstorms is far greater than in any other type of rainfall, more than one instance of rain falling for

a few minutes at the rate of 10 inches per hour having been observed in the British Isles. It has, however, been argued that, on account of the fact that the conditions precedent to intense thunder-rain are those of calm, there is a limiting value to the total precipitation in one shower imposed by the limit to the quantity of water-vapour which can be carried by a given column of air, since renewal of the supply by the advent of fresh saturated air is not occurring.[1]

Mr. W. H. Dines, however, considers that very heavy rainfalls must be due to inflowing winds, since he is of opinion that the air over any given area at any time does not contain enough water to produce them. Thus, with air at a temperature of 80° F. throughout, undergoing a fall of temperature of 10° F. per kilometre of height, which is about the average rate in the lower strata, the total water-content of a column of air would be the equivalent of 2·86 inches of rain. Allowing for inflowing winds on all sides with normal velocity, the maximum amount of precipitation which could be caused over a circular area of 100 km. radius would be 8·58 inches in a day of twenty-four hours.[2]

In extreme examples of convectional action the up-rush of heated air is sometimes so violent that it prevents the drops of water from falling until they have accumulated in sufficient quantity to overcome the resistance. This probably accounts for the occasional great intensity of heavy thunder-rain and for the large size of the drops observed. The extreme instance of this phenomenon in this

[1] See R. E. Horton on "Some Broader Aspects of Rainfall Intensities in Relation to Sewer Design," *Municipal & County Engineering* (Albany, N.Y.), June and July 1919.

[2] See *Symons's Met. Mag.*, vol. liii, 1918, pp. 95–7.

country is what is commonly known as a "cloud-burst."

If the temperature under which the condensation occurs is below the freezing-point, or if any stratum of air through which the raindrops pass is sufficiently cold, the drops become frozen and, unless re-melted, fall as hail. It often happens that hail stones after formation are caught in an upward whirl of ascending air and carried upwards into the cloud in which they originally took shape. In these circumstances a fresh coating of moisture condenses on the surface of the ice-pellet and in its turn is frozen. If the process is repeated, the hail stone becomes larger with each successive jacket of ice and may reach considerable dimensions. Large hail stones, if cut open, frequently exhibit a structure not unlike that of an onion, each coat representing one of these repeated tossings upward in its attempts to fall. Even in the most severe thunder-showers there is a maximum limit to the size which can be attained by raindrops owing to the disintegration caused by the velocity of their descent; but in the case of hailstones the only limit to size would appear to be set by the force of the ascending currents of air, and the fact that in some instances hail stones of the size of ordinary hen's eggs have fallen is sufficient to give some indication of the great upward velocity of the wind in severe thunderstorms.

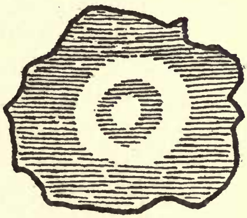


FIG. 1.—STRUCTURE OF HAIL STONE.

Convectional air-currents with a vertical component are liable to occur whenever the vertical

temperature lapse-rate varies appreciably from the normal, and whenever the expansion in ascending masses of air is sufficient to reduce their temperature below the dew-point cloud must be formed. Persistence beyond this point will produce rain, and it is probably to more or less casual inversions of the temperature gradient that rain of the type of the spring shower is due. Such showers may vary in intensity from a sprinkle to an abrupt rainfall of great intensity, and there is no rigid dividing line between them and the true summer thunderstorm-rains.

It will be observed that the phenomena giving rise to convectional rains are not directly dependent on the land configuration. So far as their physical processes are concerned, they are what are known as "meteorological" rains depending on movements in the atmosphere arising entirely from readjustment of inequalities in the distribution of temperature. There is, however, one sense in which the regional distribution of convectional rains is to some extent controlled. The most intense rainfalls of this kind appear to occur when stagnant pools of over-heated air accumulate locally. Owing to the freer play of wind-movement there is undoubtedly less probability of this happening in elevated districts than in plains or open valleys, and evidence goes to show that extremely heavy rains are less common in the hilly or normally rainy districts than the normally dry districts.

The second type of rainfall to which attention must be drawn is that commonly known as cyclonic, from its association with the passage of atmospheric low-pressure centres or barometric depressions. There is probably some general updraught of air near

the centre of such pressure systems, caused by movements in the upper air of which little is known, but the rainfall directly associated with such updraught is usually slight. Much controversy has raged in recent years round the vexed question of the origin of the common barometric depressions which constitute so prominent a feature of the climate of the temperate zones, and although the question is far from being definitely settled, modern meteorologists have been able to throw much light on their mechanism. It becomes increasingly clear that the old hypothesis of spiral whirls of air moving to a common centre of ascent needs to be fundamentally modified. It is not impossible that such a hypothesis may hold good substantially in the case of some of the minor or secondary low-pressure systems which form on the outskirts of primary depressions. Such secondaries are not infrequently associated with local rain of considerable intensity, often accompanied by electrical phenomena, and there is probably no rigid line of demarcation between rainfall of this type and that of convectional origin, with the difference that as the type merges into the cyclonic its seasonal frequency becomes more uniform, whilst the true convectional rain appears to be almost confined to the spring and summer.

Bjerknes's conception of the structure of a primary cyclonic system is represented diagrammatically in Fig. 2. The principal features arise from the interaction of two drifts of air at different temperatures, the warmer moving from the west or south-west, the cooler from south-east or east. At the line where these two drifts come into contact, the colder current forms an obstruction to the passage

of the warmer, and the air in it being denser, and therefore heavier, the comparatively light warm south-westerly wind mounts bodily over it. The ascentional motion thus imparted gives rise to thermodynamic cooling in the manner described above, and consequently to rain. It will be observed that the rain in this case will fall through the cold under-

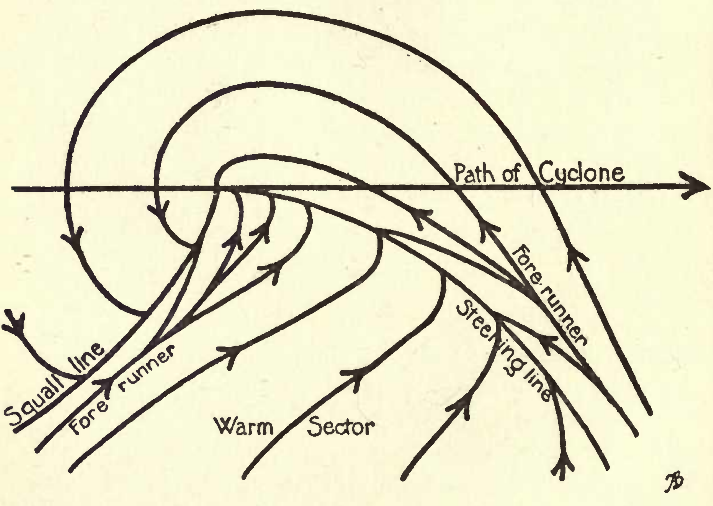


FIG. 2.—LINES OF FLOW IN A MOVING CYCLONE, AFTER BJERKNES.

cutting south-easterly wind, though in reality it is the product of the upper south-westerly wind. Rain caused in this manner is commonly steady and long-continued, and is not as a rule extremely heavy. In cyclones moving along tracks other than the normal south-west to north-east direction the quarters from which the conflicting winds blow may vary somewhat, and the most remarkable cyclonic rains

have occurred with an undercutting north-easterly or even northerly wind.

Reverting to Bjerknes's diagram, it will be observed that, after passing across the path of the warm wind, the undercutting wind is diverted to the left and, following a semi-circular track, impinges on the flank of the south-westerly current in the rear of the centre of the depression. At this stage it again operates to cause rain by cutting a way under the warmer air, giving rise to the squall-showers characteristic of the later stages of the passage of the depression. These showers are accompanied by a sudden fall of temperature and gusty north-westerly winds, and it will again be noted that the actual condensation occurs not in the air forming the cold current, but in the warm air above it.

The rainfall associated with "line-squalls" (which phenomena have been closely studied by Sir Napier Shaw and Mr. R. G. K. Lempfert) must be placed in the same category as cyclonic rainfall, although superficially it might appear more likely to be allied to precipitation of the thunderstorm type. The phenomenon in question appears to arise from the passage across the country of a flood of cold air. The characteristic changes of pressure and temperature and the occurrence of sudden showers at the moment when the front advances agree in indicating that there is a displacement in an upward direction of the warmer air by the colder, precipitation being caused in a manner analogous to that in the rear of a cyclone. Such squall-lines occasionally traverse the country with a nearly straight front, and have been traced in at least one instance for a distance of 1,000 miles.

Rainfall of a type somewhat similar to cyclonic

rain probably occurs whenever drifts of air carrying sufficient moisture move in converging tracks, and it would not appear to be absolutely necessary to predicate a difference in the temperature for ascensional movement to be propagated. Bjerknes's detailed researches on the movements of the atmosphere in relation to weather phenomena show that rain areas invariably coincide with centres of convergence. It is not clear, however, that definite cyclonic circulation is necessarily set up in these circumstances, and it is probable that some convergence frequently occurs in the prevailing south-westerly wind-drifts which sweep across the British Isles from the Atlantic Ocean giving rise to otherwise inexplicable irregularities in the distribution of the orographical rains which form the third type to which it is necessary to refer.

Orographical rains are caused by the interference of rising land in the path of moisture-laden wind, the horizontal wind being forced upward as it progresses over the surface of the sloping land. It is important to correct a misconception as to the formation of orographical rainfall which often finds a place in text-books. This is that the impinging air is cooled by contact with the cold mountain-sides. A moment's reflection shows that the reason that the ground is cooler on mountains than on plains is that it is cooled by the lower temperature of the air in contact with it. The assertion that rain is produced by contact with the colder ground is therefore tantamount to saying that the earth and air mutually cool one another—an obvious absurdity.

Orographical rains are liable to occur with a considerable range of intensity whenever sea-winds of sufficient force blow. Except on rare occasions these

rains are not very heavy, but they are extremely persistent and usually very widespread. Their great importance lies in the fact that the main controlling factor, the rising land, is always operative, and, of course, always in the same place, being, in fact, a permanent instead of an intermittent controlling cause. The great frequency of winds from the sea in the British Isles, the existence of a coast-line on all sides, and especially the concentration of the great bulk of the elevated land near the west coasts, in the path of the prevailing south-westerly winds, carrying the water they have taken up in their passage over the Atlantic Ocean, combine to render orographical rainfall far more frequent than any other in this country. Winds from between south and west blow with greater frequency than those from all other points combined, and are also liable to be of greater force than wind from other quarters. Winds blowing from the east and north have far less moisture-carrying capacity than south and west winds, and, moreover, comparatively little elevated land lies near the east coasts of the British Isles, but they are nevertheless not negligible as factors in producing orographical rainfall.

The relative frequency of these three great types of rainfall, convectional, cyclonic, and orographical, is not easily ascertained. It must be clearly understood that, although for the purpose of conveying an idea of the physical processes underlying the formation of rainfall in the various circumstances described it is necessary to consider the three types independently, under natural conditions they merge imperceptibly one into the other and more often occur in conjunction than not. Whilst it is probably unusual for typical convectional rainfall to

be found in association with purely orographical rain, cyclonic rainfall certainly frequently overlaps both the convectional and orographical types, making it extremely difficult to classify individual showers in such a way as to yield frequency data. There is, however, a well-marked seasonal fluctuation in the prevalence of both convectional and orographical rains, the former being commoner in summer and the latter in winter. Cyclonic rains are common at all seasons; they are probably rather more frequent in winter than in summer, but are individually heavier in summer than in winter.

CHAPTER III

RAIN GAUGES

The direct measurement of the amount of rainfall, sometimes referred to as the simplest of meteorological observations, is only justly so described from the point of view of the actual operation. It is fortunate that this is so, for the phenomenon of rain, in regard to its distribution in space and time, is in some respects so capricious and irregular that in order to study it successfully observations are required from a far greater number of points than suffice for any other meteorological element. Moreover, the records which are of the greatest scientific value are frequently those made in sparsely inhabited regions; it is therefore often necessary to depend upon the assistance of uneducated and sometimes illiterate observers, who do not in every case appreciate the niceties of scientific observation. The process of observing must therefore be reduced to its simplest terms, and instruments must be used as far as possible "fool-proof," and free from all complication.

A great deal of attention has been devoted to the elementary problem of devising instruments capable of yielding suitably accurate measurements in actual practice, but complete success is far from having been realized. The interference with the functioning of the gauge by wind and snow is a case in point, and the extreme importance of obtaining records

from regions at high elevations where wind and snow are of most frequent occurrence renders this disability serious. Many of the greatest difficulties have been more or less overcome, and although it is not to be assumed that the last word has been said on the subject of the improvement of the standard rain gauge as now used, or that we know by any means all that we may yet learn of the best methods of exposing it to ensure an accurate record in all circumstances, it can be at least claimed that the most palpable defects of the earliest types of instrument have been eliminated, and the objections to certain methods of exposure have been successfully diagnosed and overcome.

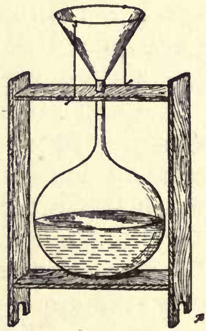


FIG. 3.—RAIN GAUGE USED AT GRESHAM COLLEGE, LONDON, IN 1695.

The earliest known actual measurements of rainfall (apart from apocryphal records in Korea in the fifteenth century) were made by Castelli in Italy in 1639. In a letter addressed to Galileo he described his gauge as a glass cylinder about 5 inches in diameter and 9 inches deep. In January 1661–2 Sir Christopher (then Dr.) Wren designed a mechanical rain gauge; and some years later Mr. Robert Hooke, of the Royal Society of London, constructed a simple funnel gauge which he exposed and observed at his official residence in Gresham College. The readings were taken by weight and the records from 1695 are still preserved. Meanwhile in 1677 Mr. R. Townley, of Townley, near Burnley, commenced observations with a gauge of which no particulars are available, except that

it was exposed on a roof and the rain-water conducted to his room by means of a long pipe. The Townley records are the earliest known in existence for the British Isles.

The standard rain gauge, as now used in the British Isles, is the result of a gradual development from earlier patterns. In principle it is unchanged from the instrument said to have been devised by Castelli, and has for its object the interception of the precipitation over a fixed area, and the accurate measurement of the collected water, which is expressed in terms of depth, i.e. the thickness of the layer of water which would have accumulated on a flat horizontal surface if none were re-evaporated nor drained away The simplest form of rain gauge would be a vessel like an ordinary jam-jar with straight vertical sides and of equal sectional area at all parts. The size of the vessel would be immaterial, since the collected water is measured only in one dimension, that of depth, and this is not

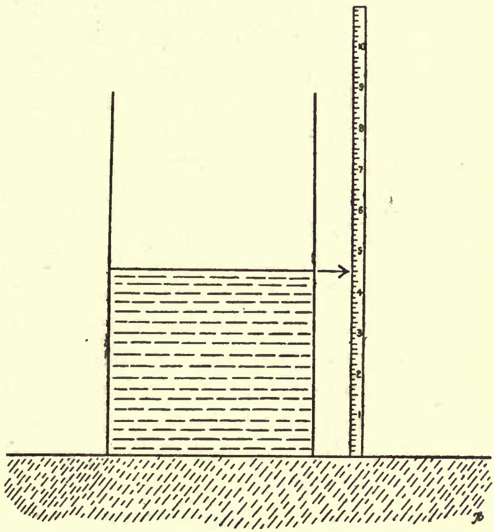


FIG. 4.—PRINCIPLE OF THE RAIN GAUGE.

affected by the other dimensions in a receptacle of uniform horizontal section. A reading of this ideal instrument would be made by inserting a rule vertically into the accumulated rain-water and ascertaining the depth by noting the length of the wetted portion. The measurement would not be capable of being made with any high degree of accuracy, and it would be necessary to make it immediately on the cessation of a shower because no provision is made for the prevention of re-evaporation, but it would serve to illustrate the principle upon which rainfall records are made. In an actual gauge evaporation is precluded, or at least reduced to a minimum, by constructing the upper part or orifice of the gauge in the form of a funnel, which allows the water to collect in the receiver below and protects it from the play of sun and air. More exact measurement than would be possible with a rule is achieved by removing the water from the receiver and pouring it into a graduated glass measure the diameter of which is smaller than that of the gauge itself, so that the depth of the water is magnified to any desired degree.

When the late Mr. Symons took up the task of systematizing rainfall observation in this country in 1859 the number of variants from the simple type of instrument described which he found in use was considerable. In all probability the attention which he drew to the subject in general led in its earlier years to an increase in diversity rather than any movement towards uniformity, and it was only after several series of exhaustive and well-devised experiments that he was able confidently to recommend any definite step towards standardization. For details of these experiments, which dealt with

not only the design of the instrument, but the size and material and, above all, the method of exposure, the reader is referred to the volumes of *British Rainfall* from 1864 to 1890, and to the summaries in the volumes for 1900 and 1906 by Dr. H. R. Mill and Mr. L. C. W. Bonacina respectively.

Whilst there can be no doubt that the above-mentioned experiments settled empirically many difficult points which had puzzled Symons, it is not quite so clear that they were directly responsible for the invention of the "Snowdon" rain gauge, the pattern on which all standard gauges are now modelled. There appears to be some difference of opinion as to the inventor of the "Snowdon" funnel, but whatever may be the origin it is clear that its introduction marked an important step in the solution of the problem of accurate rainfall recording.

In practically every early form of rain gauge the funnel introduced for conveying the rain into the receiver was placed immediately below the aperture, as shown in Fig. 5. The inability of this shallow funnel to retain snow, the loss of part of the rain owing to the rebound of drops falling with any considerable velocity, or of hail stones, and especially the formation of wind-eddies preventing raindrops from settling within the gauge were defects of a serious nature. The errors which were introduced in this way varied so much under different conditions of exposure to wind and in different kinds of weather that any attempt to evaluate them was hopeless. An additional difficulty lay in the fact that these errors were so insidious and difficult of

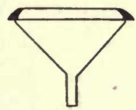


FIG. 5.—SHALLOW FUNNEL.

detection that, except under the eye of the most acute of observers, their existence was not suspected, and in consequence an immense amount of labour was expended on the compilation of records which we now realize to have been faulty.

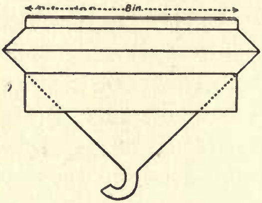


FIG. 6.—" GLAISHER " FUNNEL.

In the pattern of gauge designed by James Glaisher, the defect of the shallow funnel was overcome by carrying the walls some distance beyond the vertical cylinder of the receiver and soldering above it an inverted truncated funnel carrying the aperture of the gauge, thus forming a projecting flange as shown in Fig. 6. This method, whilst completely overcoming the objections urged against the shallow-funnel gauge, was however found to introduce other features of an objectionable nature which will be mentioned later.

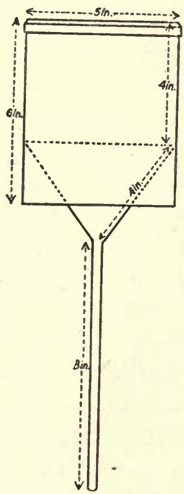


FIG. 7.—" SNOWDON " FUNNEL.

In the " Snowdon " gauge, vertical walls are carried upwards several inches beyond the funnel (see Fig. 7). The hollow cylinder above the funnel forms a sufficient receptacle for any ordinary fall of snow and at the same time reduces the risk of outsplashing and of the formation of wind-eddies to a minimum.

In modern patterns of rain gauge the aperture itself which determines the area over which the

sample of rain to be measured is intercepted consists of turned annular brass rim with a knife-edge (see Fig. 8). The diameter in standard patterns is either 5 or 8 inches, and accuracy in all diameters to at least ·01 inch is required. The material of the gauge is preferably copper, but galvanized iron or zinc forms a serviceable substitute for use in pure country air. In the vitiated atmosphere of a town almost any metal but copper rapidly deteriorates. Iron, either tinned or painted, is unsuitable, since with constant exposure it quickly rusts and the gauge becomes leaky or otherwise unserviceable.

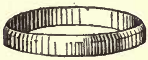


FIG. 8.—BRASS RIM.

The funnel of the gauge being of standard pattern, the construction of the remainder is a matter of less moment, the only points to which attention must be paid being the avoidance of any risk of leakage, the provision of a sufficient capacity, and the minimizing of evaporation and freezing. Any unnecessary or badly designed soldered joints should be avoided, since under the strain of constant handling they almost inevitably develop imperceptible leaks; and for the same reason the use of rivets is objectionable, since any slight play against a soft metal like copper wears it away and enlarges the socket in process of time. The capacity of the receiver must of course depend on the period for which the gauge is likely to be left without being emptied, and to some extent upon the district in which it is to be used. For the British Isles a gauge which is to be read daily should be able to hold at least 10 inches of rain without overflowing, the actual maximum fall for twenty-four hours having been 9·56 inches at Bruton, Somerset, on

June 28, 1917. In some tropical districts daily rainfalls of from 40 to 50 inches have occurred. In the drier parts of the country, with an annual rainfall of less than 40 inches, a gauge to be read once a month would be immune from risk of overflow if capable of containing 15 inches, but in mountain areas at least 25 inches should be provided, and in a few exceptional places, such as Snowdonia, the English Lakes, and part of the West Highlands from 50 to 60 inches occasionally falls in a very wet winter month. In these cases special patterns of gauge are necessary, since the provision of so unusual a capacity where not required renders the instrument unwieldy and expensive.

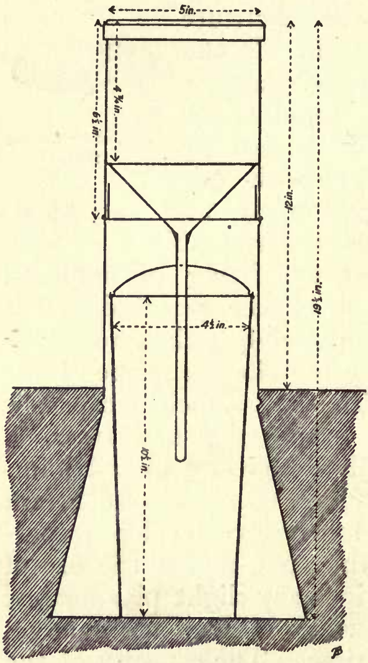


FIG. 9.—"METEOROLOGICAL OFFICE" GAUGE.

The thermal insulation of the gauge, in order to ensure the greatest possible immunity from evaporation and frost, is best secured by sinking the lower part in the ground. In very exposed positions an outer covering of felt or some other non-conducting material is a wise precaution.

In the "Meteorological Office" pattern rain

gauge (see Fig. 9) the receiver is furnished with a copper can slightly tapering in shape, so that in case of frost the joints are unlikely to be strained. In the "Snowdon" pattern (see Fig. 10) there is a straight-sided inner can, and within it a stout glass bottle with a narrow neck into which the

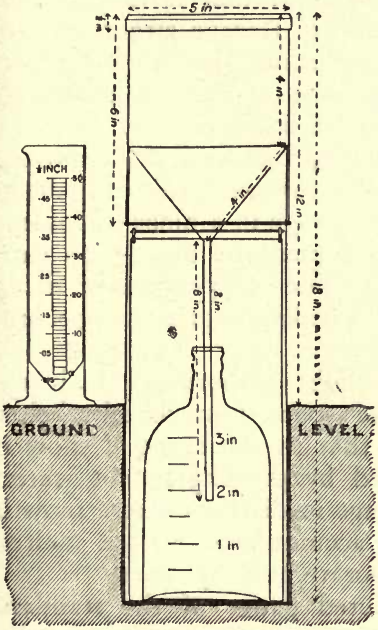


FIG. 10.—"SNOWDON" GAUGE.

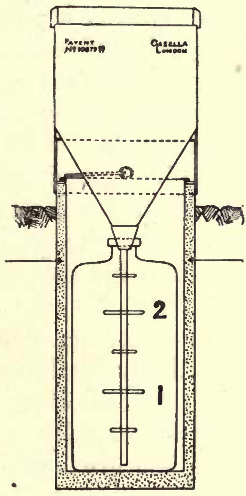


FIG. 11.—CASELLA'S INSULATED SNOWDON. THE STIPPLED PORTION CONSTITUTES THE AIR-JACKET.

pipe from the funnel is inserted. An improved gauge recently introduced by Messrs. Casella & Co. presents the additional advantage that the inner can is suspended from a narrow metal collar soldered on the inner side of the outer casing, so that it is entirely surrounded by an air-jacket; a great

measure of immunity from evaporation and freezing is secured.

The standard rain gauge, of which Figs. 9, 10 and 11 are examples, is characterized by extreme simplicity of construction, the number of soldered joints being kept to a minimum, and in every possible case being so planned that no unequal strain falls upon them in daily use and that if they should become defective no risk of leakage either inwards or outwards is likely to occur. In the " Meteorological Office " gauge the outer can is slightly splayed so that it can be fixed securely into the ground without becoming dislodged in removing the funnel. With the " Snowdon " this can best be done by embedding the gauge in a block of cement or in the interior of a piece of drain-pipe sunk flush into the ground. The old practice of fixing a gauge by means of wooden pegs is not recommended.

In some gauges a slight elaboration is introduced by making the space immediately below the funnel hollow, so that in the event of snow it may be rapidly melted by pouring in hot water. This is a great advantage in districts where snow is frequent, since if the accumulated mass is melted slowly, it is apt to evaporate in the process.

A properly constructed gauge of the standard pattern, made of copper, well fixed and carefully used, should be capable of lasting and retaining its accuracy for half a century, and even gauges of galvanized iron, especially when painted on the outside from time to time, should remain in good condition for thirty years. It is undesirable to paint the *inside* of the funnel, since the surface of the paint in time becomes spongy and absorbent.

To make a reading of the gauge it is necessary to remove the funnel, which fits closely over the lower outer can, and to pour the accumulated water into a graduated glass measure. The diameter of the measure being made smaller that that of the funnel of the gauge, any desired magnification of the scale can be obtained, and no difficulty is experienced in obtaining measurements accurate to ·01 inch or 0·1 mm. Any further refinement of the measurement is unnecessary for ordinary purposes, and is, as a rule, meaningless. There should, however, be no difficulty in graduating the glass to an accuracy of ·001 inch, and this is desirable, although the readings are only taken to ·01 inch. In order to give an open scale, the glass measure for a 5-inch gauge should not exceed about 1·5 inch in internal diameter and for an 8-inch gauge about 2·0 inches. Glasses with these diameters respectively, would be inconveniently long and liable to be broken if made to contain more than ·50 inch of rain, and this capacity is usually adopted. In case of a greater fall of rain it is therefore, of course, necessary to fill the glass to the ·50 inch mark as many times as required, and then measure the residue, subsequently adding together all the amounts measured.

Since the units of measurement for readings in inches and millimetres are respectively ·01 inch and 0·1 mm., the correct practice in measuring very small falls is to ascertain whether they reach half-unit measurement, i.e. ·005 inch and 0·05 mm., respectively; if less than this amount, the few drops of water should be thrown away and the day entered as rainless; if more than this and less than the unit amount, the reading should be entered as ·01 inch or 0·1 mm. respectively. The number of days on

which rain is recorded thus depends in an important measure upon the accuracy of the lowest graduation mark. In glasses with flat bottoms, as shown in Fig. 12, it is often very difficult to determine this point with certainty and a very slight personal bias on the part of the observer may make a serious difference in the number of days with rain recorded. In the "Camden" pattern of measure (Fig. 13), this difficulty is to a large extent overcome by tapering the glass at the bottom, thus spacing out the lowest graduations. An additional graduation mark for the half-unit is added below the unit graduation, enabling the decision as to whether a small fall should be entered or not to be made with ease and certainty. This pattern of glass appears to have been introduced first in Germany, and the same principle is adopted in a somewhat different form in the Norwegian meteoro-

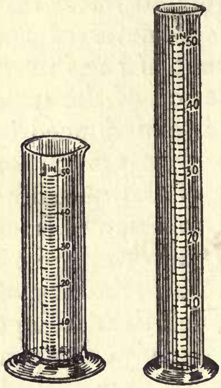


FIG. 12.—FLAT-BOTTOMED MEASURING GLASSES.

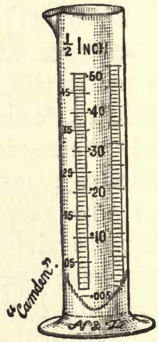


FIG. 13.—"CAMDEN" MEASURING GLASS.

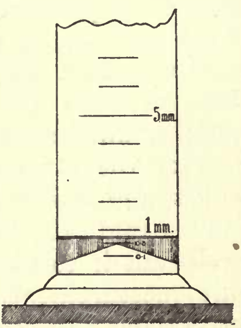


FIG. 14.—MEASURING GLASS — NORWEGIAN PATTERN.

logical service, by the use of a measuring glass in which the magnification of the lowest graduation mark (in this case 1·0 mm.) is made by means of a small glass cone at the bottom (see Fig. 14).

The glass measure should preferably be constructed of crown glass of good quality and of even transparency. With very thick or slightly opaque glasses a distortion of the line of vision renders the exact position of the surface of the water difficult to determine. In a narrow glass the true water-surface, of course, takes the form of a meniscus, or slight concavity, and the measurement should always refer to a line tangential to the bottom of the curve. Care must be exercised, however, in cases

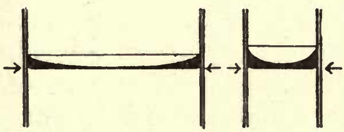


FIG. 15.—MENISCUS.

FIG. 16.—FALSE MENISCUS.

of slight distortion to detect the true bottom of the meniscus : this is often seen as a black line between two fainter apparent surfaces. The importance of carefully making allowance for distortion is apparent when it is remembered that a systematic error of, say, ·005 inch in every daily reading will give an error of about 1·00 inch in the course of a year.

As a check upon the accuracy of the daily readings it is desirable whenever possible to place a second gauge beside that read each day and to make a reading once a week or once a month. For this purpose, or for monthly readings at stations where a daily visit is impracticable, especially if in regions of heavy rainfall, gauges of larger capacity than the "Snow-

don" are usually required. Two standard patterns are in use, the "Bradford" and the "Seathwaite," the latter being designed for use only in exceptionally wet localities.

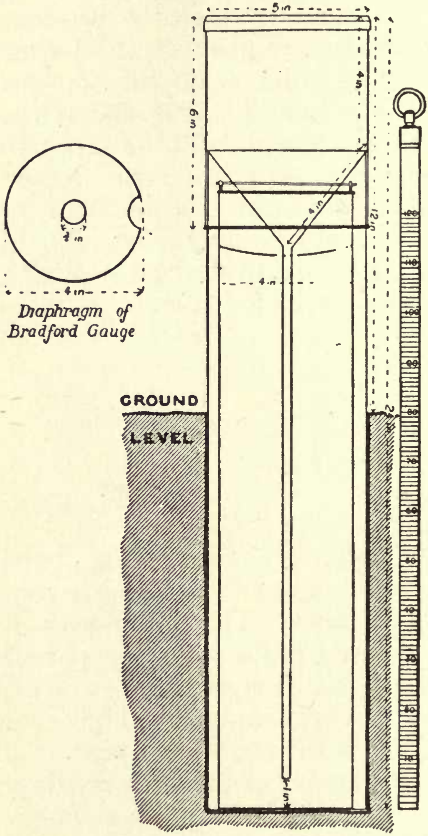


FIG. 17.—"BRADFORD" GAUGE.

The "Bradford" rain gauge (Fig. 17), originally designed for use at the moorland stations of the Bradford Corporation Waterworks in Yorkshire, is identical with the "Snowdon" in respect of its funnel, but the lower can is lengthened to give any desired capacity. The gauge is sunk in the earth so that it projects 1 foot, and the depth to which the lower part is buried usually secures immunity from freezing. This gauge contains no bottle, but an inner metal receptacle covered by a diaphragm pierced to allow the pipe from the funnel to enter and also to allow the

water to be poured out for the purpose of measurement. A cedar-wood rod tipped with brass is provided, graduated suitably to the diameter of the inner can, and when a reading is desired the first step is to make a preliminary measurement by dipping the rod into the water and reading off the amount by noting the portion wetted. This reading is taken only to the nearest ·10 inch. The water is then poured into a measuring glass and measured as in the case of the daily gauge. The glass is usually made to contain 1·00 inch and graduated to ·10 inch, but accuracy to ·01 inch is easily obtained, if desired.

The "Seathwaite" gauge (Fig. 18) was specially designed by Dr. H. R. Mill for use in remote mountain areas where exceptional rainfalls may be looked for, and where, owing to snow, it is sometimes impossible to make visits even every month. The funnel is 5 inches in diameter at the orifice and is splayed to a diameter of 8 inches where it fits over the lower can. A locking device prevents it from being tampered with by any unauthorized person removing the funnel. The lower can, which is about 14 inches deep, is double, forming a casing, and the space between the sides is packed with felt to minimize the risk of damage by frost. Within this double outer body is a second can which holds the accumulated water. The gauge is provided with a metal "dipper," suggested by the late Mr. Gethin Jones, consisting of a narrow-necked and flat-bottomed vessel with a long handle holding exactly 5 inches of rain-water when full to the brim. Before reading, a preliminary rough measurement is taken with a rod, as in the "Bradford" gauge. In making the exact reading the dipper is immersed in the water and withdrawn as often as it is completely filled, each fill repre-

senting, of course, 5·00 inches. When it is no longer possible completely to fill the dipper by immersion, it is laid aside and the inner can drawn out, the small residue of water being measured by a glass in the

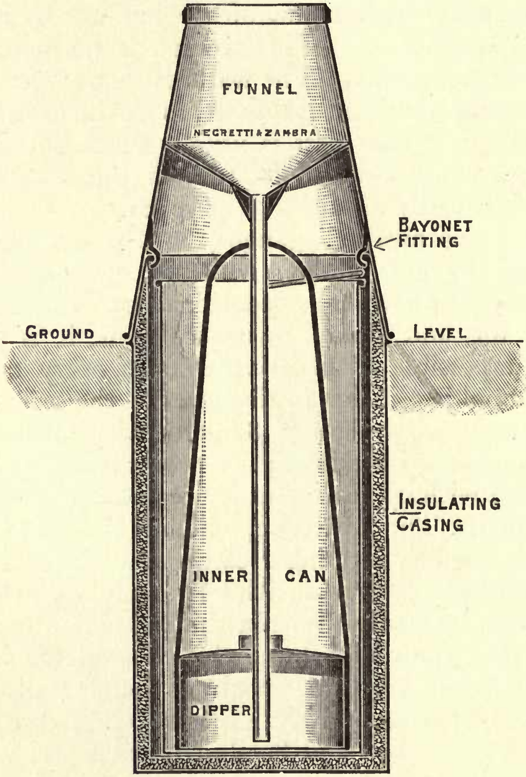


FIG. 18.—"SEATHWAITE" GAUGE.

usual way. It is advisable to test the capacity of the dipper from time to time, as any dent will affect its accuracy. One of these gauges has been in use on the Stye, Cumberland, for some years, a district

in which as much as 50 inches of rain sometimes falls in a single month, and where heavy snow and severe frost are of frequent occurrence, and has given satisfactory results.

The adoption of the standard rain gauge for use in the British Isles is largely due to the exhaustive experimental work carried on under the direction of Mr. Symons during a period of nearly thirty years between 1860 and 1890. Observations were made by Colonel Michael Foster Ward at Castle House, Calne, in Wiltshire, commencing in 1863, and simultaneously by Rev. J. Chadwick Bates at St. Martin's, Castleton Moor, near Manchester. In 1865 Mr. R. Chrimes set up an elaborate collection of experimental gauges on the flat roof of the Boston Reservoir, Rotherham, and in the following year Rev. T. E. Crallan undertook the observation of a series of gauges at Hurst Green, Sussex, the latter being designed to test the material best suited for the construction of the gauge. About a year later Mr. Crallan's set was handed over to Rev. C. H. Griffith, of Stratfield Turgiss, near Reading. To him afterwards were sent the various experimental gauges which Mr. Symons had had in use since 1863, and four years later, when Colonel Ward left Calne, the whole of the gauges in his charge were also sent to Stratfield Turgiss. A separate series was established at Aldershot in 1869 in the care of Sergeant Arnold.

In 1870 the Stratfield Turgiss gauges were handed over to Rev. F. W. Stow, of Hawsker, near Whitby, in order that the experimental readings might be repeated in the more exposed climate of the north, a precaution which experience showed to be of great importance, though from the point of

view rather of exposure than of the pattern of gauge. These observations will be mentioned later.

In 1872 the Rotherham experiments were completed, and in 1875 the Rotherham Corporation undertook the charge of the gauges and had them erected on the bank of the Ulley Reservoir; these gauges, like those at Hawsker, also gave invaluable information rather from the point of view of exposure than any other. The records were kept up with certain modifications until 1890, and form one of the most conclusive pieces of deliberate scientific research on rainfall observation ever carried out.

Further experiments on the size and position of gauges were commenced in 1877 by the late Mr. George Dines, and in 1881 a complete discussion of the results, together with those of previous observations, was undertaken.

The detailed description of the various series and the conclusions to which they led are published in the annual volumes of *British Rainfall*.

OBSOLETE PATTERNS OF RAIN GAUGE

The several series of investigations pointed conclusively to the superiority of the "Snowdon" type of gauge, and it is a matter for regret that many of the older patterns are still to be found in use, and even more unfortunate that they are still sometimes manufactured and sold to the uninstructed. The defects of these gauges are of importance, because it is often necessary to utilize records made with them when no others are available, and because nearly all the records of more than fifty years ago must be accepted with caution as liable to be to some extent vitiated. As will be shown later, the magnitude of the error in results caused by the use of

non-standard instruments depends largely upon the conditions under which they are exposed, and information on this point is too often lacking. In comparing records of early periods with modern observations, great care must be exercised on this account.

The principal types of obsolete rain gauge are: (i) the "Howard" gauge, invented by Luke Howard, the well-known student of cloud forms, and compiler of early statistics of the climate of London; (ii) the "Fleming" and other float-gauges; (iii) the "British Association" gauge, sometimes known as the "Symons" gauge, although discarded by Symons at an early stage of his investigations; (iv) the side-tube gauge; (v) the Glaisher gauge, designed by James Glaisher; (vi) rectangular gauges; and (vii) tap-gauges.

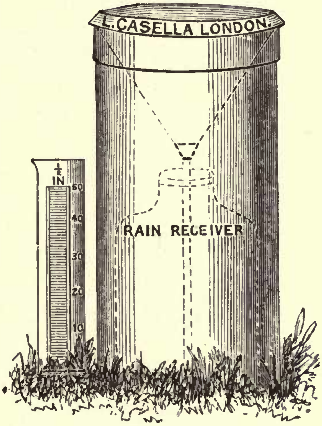


FIG. 19.—"BRITISH ASSOCIATION" GAUGE.

In practically all the early patterns, as already mentioned, the shallow funnel was a fundamental defect. In the "Howard" and "British Association" gauges a further disadvantage was inadequate size, not only leading to overflow in case of unusually heavy rain, but precluding the sinking of the lower part of the gauge in the ground, thus involving risk of evaporation by over-heating, or of bursting by frost. Howard's gauge, which consists of a simple funnel fitted over the neck of a bottle by a metal

collar, presents a peculiar defect. This collar not infrequently becomes partially detached owing to the strain of constant removal, especially when frozen, and when this occurs, raindrops running down the outside of the funnel find their way through the crack (see point marked in Fig. 20) and enter the receiver, thus unduly increasing the amount of water caught. In the Jagga Ráo gauge (see p. 53) this risk was obviated by the provision of a little metal hood (see Fig. 27). A similar source of error affects

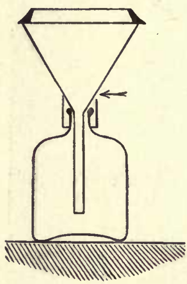


FIG. 20.—"HOWARD" GAUGE.

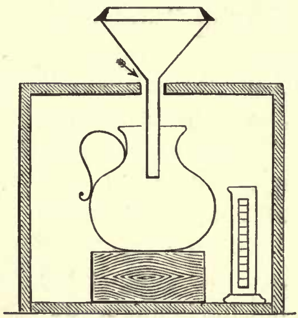


FIG. 21.—BOX GAUGE.

certain patterns of box-gauge (see Fig. 21), and is particularly troublesome in the "Glaisher" gauge, which is otherwise a very good pattern. It is not at all easy to detect the first symptoms of leakage in the Glaisher gauge, and numerous instances have been brought to notice in which serious errors have arisen through this cause. In extreme cases the collar fitting over the receiver falls away altogether, so that the funnel rests upon the lip of the receiver, and any slight distortion of the metal, in either the funnel or the can, forms an aperture for the illegitimate entrance of rain which has run down the outer

face of the funnel, and of blown raindrops which strike the gauge at the point of leakage.

Dr. Mill, in his paper "On the Best Form of Rain Gauge,"[1] gives an interesting example of the effect of the progressive deterioration of uncared-for Glaisher gauges. A number of Glaisher gauges which had been condemned on inspection as defective were continued in operation for some years together with the Snowdon gauges, which had been set up alongside to test the extent of their inaccuracy. Three gauges of the group, A, B, and C, were sound, but one of these (A) gave small readings for another reason. The remainder, D, E, F, G, and H, exhibited the defect described. The records during six years are given in the following table:

Year.		1901.		1902.		1903.		1904.		1905.		1906.	
Gauge.		Glaisher.	Snowdon.	Glaisher.	Snowdon.	Glaisher.	Snowdon.	Glaisher.	Snowdon.	Glaisher.	Snowdon.	Glaisher.	Snowdon.
		in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.	in.
Sound	A .	27·5	28·1	26·1	28·0	43·3	45·5	32·2	34·7	31·3	34·3	35·8	39·0
	B .	26·4	26·3	25·4	25·4	47·3	48·8	29·6	29·6	27·2	26·8	31·2	30·7
	C .	31·9	31·2	28·3	27·6	55·2	54·6	32·5	32·2	30·8	30·6	36·7	36·6
Defective	D .	33·7	31·7	32·6	30·0	62·6	57·8	34·5	31·7	33·2	29·9	38·6	36·4
	E .	32·6	30·9	29·2	25·7	62·7	46·8	41·6	28·3	34·0	24·3	38·2	28·7
	F .	32·7	26·6	29·7	25·1	58·7	47·3	36·1	28·9	30·5	24·8	37·6	29·7
	G .	25·9	27·3	24·5	25·4	48·4	47·7	32·2	29·9	34·4	27·4	36·6	30 6
	H .	27·7	26·8	27·8	27·1	49·0	49·3	31·4	31·2	33·9	28·5	41·0	26·7
Mean D to H .		30·5	28·7	28·8	26·7	56·3	49·8	35·1	30·0	33·2	27·0	38·4	30·4

Expressing the mean value for the five defective Glaisher gauges, D, E, F, G, and H, as a percentage of the mean value for the five Snowdon gauges at

[1] *Q.J.R. Met. Soc.*, vol. xxxiii, pp. 265–74.

the same stations, the progressive nature of the error is apparent.

	1901	1902	1903	1904	1905	1906
Mean D to H .	106	108	113	117	123	128

The increase will be seen to be nearly uniform, but, of course, the varying circumstances surrounding individual cases render it unsafe to apply corrections arrived at from any such comparison.

The "Fleming" gauge, at one time used extensively in Scotland, and occasionally still met with,

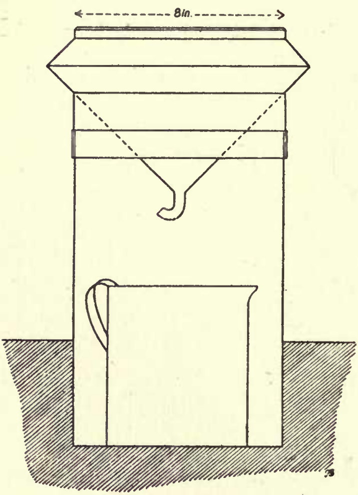


FIG. 22.—"GLAISHER" GAUGE.

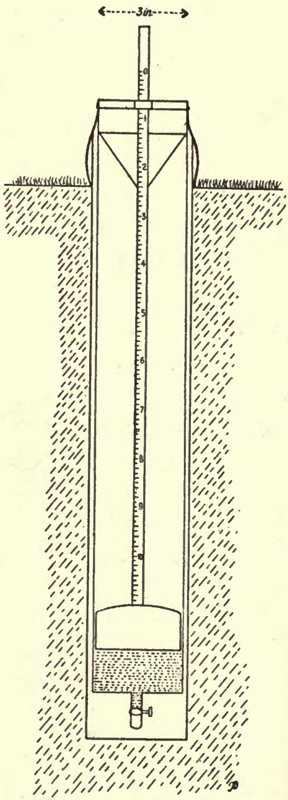


FIG. 23.—"FLEMING" GAUGE.

was designed with a view of enabling a direct reading to be obtained without the use of a measuring glass.

The gauge itself is 3 inches in diameter and is fitted with a funnel not unduly shallow in design. Within the receiver is a hollow copper float to which is attached a thin strip of metal passing upwards through the orifice of the funnel and graduated for the purpose of reading off the amount of water collected. When any considerable fall of rain has occurred, this measuring-rod must naturally project some distance beyond the lip of the funnel, and in these circumstances the rain-drops which strike against it run down and enter the gauge, which thus in effect has a collecting surface greater than the three-inch circle upon which the graduations are founded. It is on record that one of the great corporation water-supply schemes was based upon rainfall records made by Fleming gauges, and the compensation water granted was on that account so far in excess of the proper amount that it was eventually found to be necessary to buy it off for £120,000—a striking comment on the need for caution in the matter of rain gauge design. In common with all other float-gauges, the Fleming gauge further suffers from the defect that the float is apt in time to become dented, or even to leak, in either case failing to function properly.

Even apart from these sources of error, the Fleming gauge is capable only of very rough measurements, since, unless the float-chamber is extremely narrow, and thus of reduced capacity, the magnification of the scale is very slight. The same remark applies to gauges of the side-tube variety, designed to give a reading by means of a glass tube attached to the side and connected with the receiver so that the depth of accumulated water can be read off directly. These gauges are extremely liable to develop leaks

at the joints and invariably become useless in frost.

Gauges fitted with taps for drawing off the water are objectionable on account of their invariable tendency to drip when worn, causing loss of part of the catch. They present no compensating advantage, and should on no account be used.

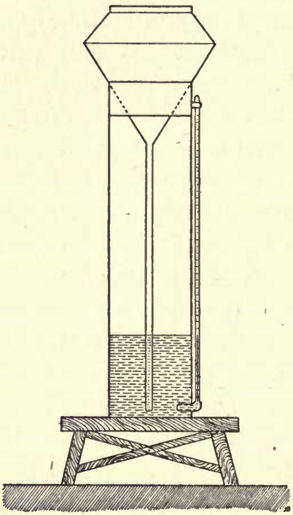


FIG. 24.—SIDE-TUBE GAUGE.

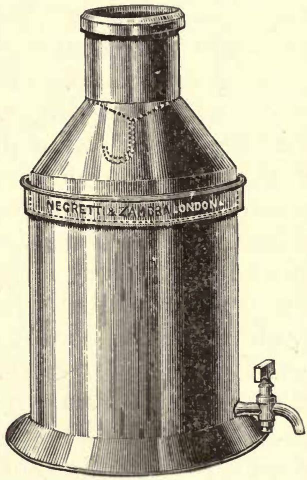


FIG. 25.—TAP GAUGE.

Against the use of rectangular gauges no very strong argument can be adduced. Their principal defect lies in the presence of unnecessary soldered joints, any of which are liable to become leaky, and in the greater risk of distortion by frost. It is also much more difficult to ensure accuracy in the size of the funnel aperture than in the case of the circular gauge.

In the *Quarterly Report of the Scottish Meteoro-*

logical Society, April to June 1861, Mr. Walter Elliot described a gauge of considerable ingenuity designed by G. V. Jagga Ráo, of Vizagapatam, and a few specimens are to be found extant. The idea of the Jagga Ráo gauge was to make the aperture of the funnel, which was circular, exactly 4·697 inches in diameter, i.e. with a receiving surface of 17·33 square inches. In the absence of a measuring glass the reading might be made by means of an apothecary's measure, 1 fluid ounce being equivalent to ·10 inch of rain. A considerable number of these gauges were at one time in use in Madras for the purpose of official records. To the gauge itself there is no special objection apart from its shallow funnel, but the slight difference in size from the standard gauge of 5 inches in diameter gives rise to the risk that it may be used with a measuring glass graduated for a 5-inch gauge, causing a constant error of 12 per cent. in the readings. A similar kind of error arose in a gauge at one time put on the market with a diameter of 5·05 inches, the object being to make the receiving area precisely 20 square inches and enable the measurement to be made in cubic inches. The use of a 5-inch measuring glass in this case gave rise to an error of 2 per cent.

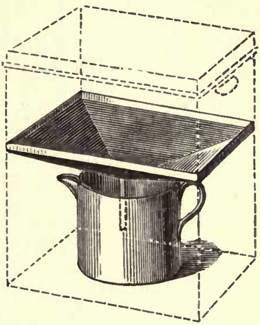


FIG. 26.—RECTANGULAR GAUGE.

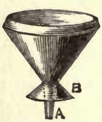


FIG. 27.—FUNNEL OF JAGGA RÁO GAUGE.

CHAPTER IV

THE EXPOSURE OF RAIN GAUGES

One of the most insidious dangers in dealing with rainfall records arises from the impossibility of ensuring in all cases that the exposure of the gauge is such that its indications will accurately represent the amount of rain falling at the spot. Attention has already been given in the preceding chapter to the precautions which experience has shown to be necessary in the design of the gauge. The difficulty of securing uniformity in this respect has also been touched upon, but these difficulties are not insuperable and will probably be overcome in the course of time. The problem of correct exposure is, however, of a different order. More or less invariable rules can be laid down for the avoidance of certain faults of exposure common to all situations, but to a very large extent the conditions must be determined by local circumstances; in other words, instead of laying down a rule we must enunciate a principle, and even were it possible to condense such a principle into simple terms for the guidance of uninstructed persons commencing rainfall recording, there are certain circumstances in which a perfectly satisfactory site is probably unattainable.

When Mr. Symons first undertook the systematization of rainfall recording in the British Isles, he found, besides a multiplicity of different kinds of

gauge in use, an almost equal variety of method, or want of method, in exposing them. The discordance in the records brought together at that time, which becomes apparent when any investigation involving critical examination of the data is made, is undoubtedly mainly due to this cause.

A great deal of important information on this head was gained from the experimental observations referred to in Chapter III. The principal point to which attention was devoted was the effect of placing gauges at different heights above the ground. It had previously been noticed that a diminution of catch resulted from elevating the gauge, and although at that time the reason of the phenomenon was not clearly understood, a systematic attempt was made to determine the ratio of the amount measured at different elevations, no doubt with the idea of arriving at a means of adjusting records taken at various heights and thus bringing them into harmony. Although in the course of the experiments it became clear that the rate of falling-off of the catch with height was not uniform, depending less upon the elevation than on the conditions of exposure to wind,[1] so that the experimental results are not of general application, it is not without interest to summarize some of the conclusions arrived at.

[1] It is fair to point out that various observers had insisted on this explanation of the discrepancies at much earlier dates. In a paper written in 1858 by the late Dr. James Stark, then Secretary to the Scottish Meteorological Society, the effect of wind on elevated rain gauges is discussed, and the writer mentions that his view that the deficiency of catch in elevated gauges was caused by wind was put forward as early as 1821 by Captain G. Mackenzie, and later by Professor Stavelly and Thomas Stevenson. Stanley Jevons strongly insisted on the same view in papers written in 1861 (*Phil. Mag.*, 1861, **22**, p. 421 ; *Brit. Ass. Report*, 1861, Pt. 2, p. 62).

Colonel Ward's observations at Calne with gauges elevated on poles, during the four years 1863 to 1867, showed that at 5 feet above the ground the amount measured was 97 per cent. of the amount at 1 foot, and at 20 feet 94 per cent. Mr. Chadwick Bates's observations at Castleton from 1863 to 1866 gave respectively 95 per cent. and 89·5 per cent. on the average. In both cases it was observed that the ratio was not steady and the variations of wind-velocity were clearly the determining factor. The results obtained at Stratfield Turgiss by Mr. Griffith confirmed the previous experiments in regard to pole exposures, with the important addition that experience was gained as to the effect of placing gauges on sloping roofs. On the average of three years the gauge at 20 feet on a pole caught 93 per cent. of that at 1 foot; one placed at 23 feet above the ground on the ridge of the roof of a barn gave 77 per cent. of that at 1 foot, and another at 39 feet on the roof of the Rectory 74 per cent.

The experiments on the effect of elevation were logically pursued in the fine series of observations at Rotherham, at first by Mr. Chrimes and afterwards by the Rotherham Corporation, and Mr. Symons was able to deduce conclusively that the diminution in the measurement by the elevated gauges was caused directly by the sweep of the wind.

The Rotherham experiments were made more complete by the observation of a number of inclined gauges, specially designed to indicate the effect of wind. These included one with five funnels, one horizontal and four vertical, one facing each of the cardinal points, so that the relative amount of rain falling vertically and from each direction respectively was indicated. There were also four gauges

inclined at angles of $22\frac{1}{2}°$, $45°$, $67\frac{1}{2}°$, and $90°$ respectively, each mounted on a vane so as continually to face the wind; and one elaborate instrument in which the funnel, besides always facing the wind, was automatically varied in inclination so that the orifice was kept at right angles to the path of the falling rain. In addition to the gauge measurements, observations of the force and direction of the wind

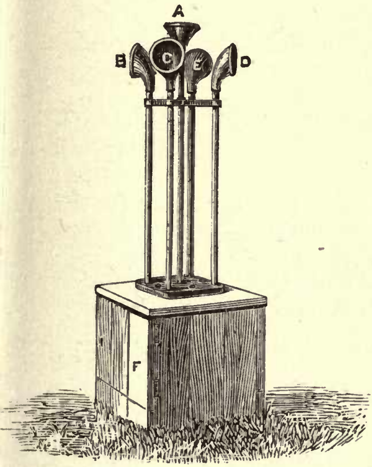


FIG. 28.—FIVE-FUNNELLED EXPERIMENTAL GAUGE.

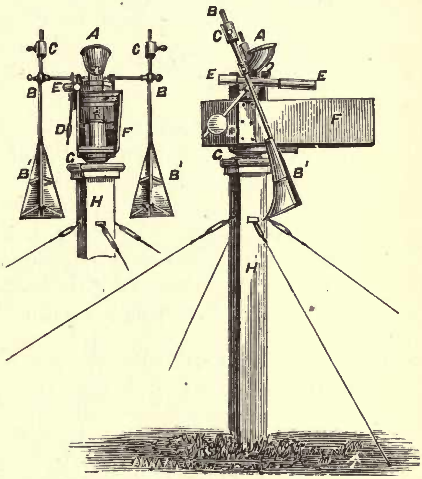


FIG. 29.—TILTING EXPERIMENTAL GAUGE.

were made separately by means of anemometers. The loss in the elevated gauges was shown to vary seasonally with the seasonal change in wind-velocity, and also incidentally with the daily variations. The final generalization, showing the percentage of rain at 25 feet compared with 1 foot with wind blowing at different velocities and rain falling at differing inclinations to the vertical is extremely illuminating:

Angle of rain	0°—35°	35°—40°	40°—75°
Wind, miles per day . .	104	144	187
Amount of catch at 25 feet per cent. of catch at 1 foot .	90	89	79

The conclusions arrived at were borne out, and further important points noticed in regard to roof exposures, by independent investigations carried out by Mr. George Dines on a tower 50 feet high at Walton-on-Thames. Mr. Dines's results are summarized as follows :

(1) One gauge only, placed on a building, cannot be depended upon to give the amount of rain falling at the same elevation above the ground.

(2) Of two gauges, somewhat similarly placed, that which is farthest removed from the windward side of the building will collect most rain.

(3) The greater the force of the wind, and the smaller the size of the raindrops, the greater is the difference between the rain collected in a gauge upon the ground and one elevated above it.

(4) On occasions when there is no wind, the rain collected at an elevation of 50 feet is equal to that collected on the ground.

Mr. Symons, in his general summing up, adds one or two additional observations :

" Although the actual total falling at, say, 25 feet above the ground may really be slightly less than that at 1 foot, the greater part of the decrease in the amount collected is due to the eddies produced by the rain gauge funnels, and by the buildings on which they are placed.

" The less the diameter of the elevated gauge the less will it indicate ; the larger the gauge, or the more it is protected from the direct impact of the wind, the more will it indicate."

The practical outcome of these inquiries was the adoption of the rule that rain gauges should be exposed with the top of the funnel at a height of one foot above the ground. This rule, once decided upon, was rapidly brought into general use. In *British Rainfall*, 1863, the number of records printed

from gauges at from 9 inches to 1 foot 3 inches above the ground was only 13 per cent. of the whole. In 1891 the percentage had risen to 59, and in 1919 to 68. In the same three years the percentage of gauges at 10 feet or more above the ground was respectively 7, 2, and 1.

It is to be observed that the British practice in this respect is at variance with the continental, exposure at 1 or 1·5 metre being recommended in most countries of Europe. Apparently the only valid objection which has been urged to the exposure of gauges at one foot is that in case of deep snow the instrument may be completely buried. Whilst the risk of this occurring on rare occasions is no doubt obviated by elevating the gauge, it appears to have been overlooked that the loss of catch occasioned by elevating the gauge is, as a rule, far greater in snow than in rain, and except possibly in localities where deep snow frequently falls, or in which drifts are of common occurrence, the remedy is worse than the disease.

The experimental series of rain gauge observations by Rev. F. W. Stow, at Hawsker, which were supplementary to the work of Rev. C. H. Griffiths at Stratfield Turgiss, shed valuable light on another aspect of the problem. Mr. Stow erected a set of gauges at heights of 1 foot, 5 feet, and 10 feet, with their receiving surfaces in a vertical plane, and so arranged that they were rotated by means of vanes so as constantly to face the direction of the wind. Each of these gauges was paired with a horizontal mouthed gauge at the same elevation. The results showed that whilst the gauges with horizontal funnels caught less with increased elevation, those with vertical funnels caught more, the decrease and

increase respectively being roughly proportional, and having approximately the same seasonal variation. This result was clearly brought about by the increased deviation of the paths of the raindrops from the vertical at greater elevations.

The most important factor in the situation to which Mr. Stow was able to draw attention was, however, the effect of inequalities in the contour of the ground upon the catch of gauges even when exposed at the standard height of 1 foot. Thus the amount found in a gauge on the summit of a knoll was smaller than that in a gauge in a sheltered situation, and in a gauge on a sloping hillside the catch was diminished when the wind blew in such a direction as to be forced up the slope. A gauge set at the edge of a lofty cliff overlooking the sea was found to indicate 91 per cent. of the true fall when the wind was blowing from the land, and no more than 62 per cent. when the wind was blowing from the direction of the sea.

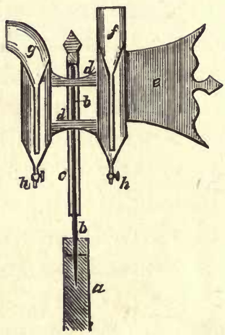


FIG. 30.—ROTATING EXPERIMENTAL GAUGES.

The inference which Mr. Stow quite justifiably drew from these facts was that any upward deflection of the wind in the immediate neighbourhood of the gauge appreciably aggravated the formation of eddies round the funnel, and thus hindered the drops from settling in the gauge. This hypothesis, which subsequent experience has fully confirmed, gave rise to considerations beyond those of mere elevation in selecting suitable exposures for rain gauges. It is

clear that the defect in the catch of rain in the case of gauges exposed under conditions such as those described increases with increase in the average wind-velocity, and thus sites which would, *ceteris paribus*, be tolerable in a sheltered valley may be extremely unsuitable near the sea or in a high, windy situation. The diminution in the amount measured in gauges placed at more than 1 foot above the ground becomes increasingly greater in such circumstances. Should the gauge used be of a non-standard pattern, with shallow funnel, all defects due to wind-eddies are aggravated, and in extreme cases the record becomes quite useless.

Whilst neglect of the points to which attention has been drawn are largely responsible for errors in the measurement of the fall of rain, it is in respect of the measurement of snow that they are of the most vital importance. Owing to their relatively less density and greater liability to be carried by the wind, snow-flakes are much more affected by wind-eddies than are raindrops, and since snow is of more frequent occurrence in upland districts where the wind in winter often attains a high velocity, the greatest precaution is necessary in selecting a site for a gauge in such localities.

Apart from the improvement of the gauge itself, of which some account has already been given, considerable attention has been paid to the design of various types of protectional devices for reducing the play of wind in the neighbourhood of the gauge. The greater liability to snow in certain parts of continental Europe, particularly Russia and Northern Germany, than in the relatively mild climate of the British Isles, has led to more attention being given to this question abroad than at home; but the

importance of obtaining accurate information as to the true amount of precipitation in the upland areas of this country, of which snow forms no insignificant part, makes it a matter for regret that British meteorologists have not given more attention to the subject.

One of the most successful simple forms of wind protection is the Nipher shield invented by Professor F. E. Nipher, of St. Louis. This consists of a metal jacket surrounding the body of the gauge. The diameter of this jacket varies from that of the gauge itself at the bottom to four or five times that diameter at the top which is level with the receiving surface of the funnel. The object of this contrivance is to prevent upward currents of air in the immediate vicinity of the gauge and thus to minimize the formation of wind-eddies. In some patterns the jacket itself is made of fine wire-netting, which is found to be nearly as efficacious as solid metal in reducing eddying and is less liable to cause insplashing from rebounding raindrops. In other patterns the inner surface of the jacket is covered with wire-netting for the same purpose. Some difficulty is experienced with the apparatus owing to the liability for snow to accumulate in the space between the jacket and the gauge, but numerous experiments have testified to its general efficacy in regard to the function for which it is intended. Fig. 31 shows the shield used in the Norwegian Meteorological Service. An improved form of Nipher shield has recently been introduced in Switzerland by Billwiller (see Fig. 32), and experiments are now being made with a view to designing a shield for use in this country.

Among the distinguished meteorologists who have

experimented widely with wind-protection devices, the chief place must be given to Dr. von H. Wild, of the late Russian Meteorological Service, who read an important paper on the subject before the St. Petersburg Academy

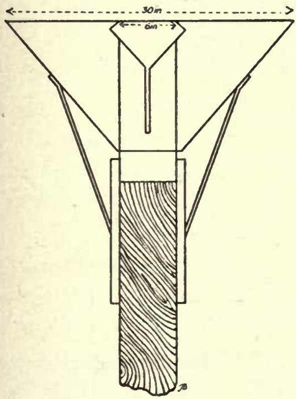


FIG. 31.—NIPHER SHIELD—NORWEGIAN PATTERN.

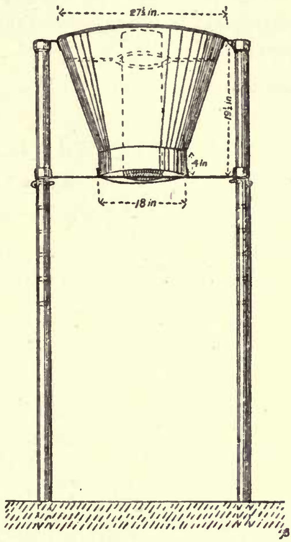


FIG. 32.—BILLWILLER'S DESIGN FOR NIPHER RAIN GAUGE SHIELD.

in April 1885. In his experimental work in Russia Wild observed a series of elevated gauges and found

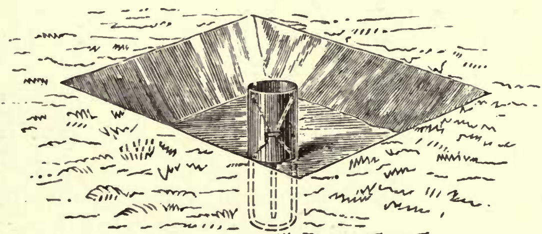


FIG. 33.—GAUGE SUNK IN PIT.

the diminution of rainfall with elevation to be far greater than had been found in England. He

attributed this result to the greater frequency of snow. He therefore established a gauge sunk in a pit, as had been previously tried by Colonel Ward at Calne, and was led to the opinion that, provided such a gauge can be efficiently protected from snow-drift, it will indicate the true fall more readily than an exposed gauge. At a later stage of his experiments Wild attached Nipher shields to the whole series of gauges (except the pit gauge), and carried out a rigorous comparison between this form

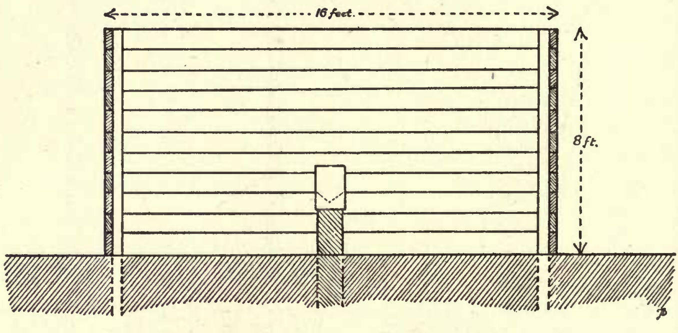


FIG. 34.—SECTION OF WILD'S FENCE.

of protector and a simple fence enclosure. The latter was composed either of solid woodwork or interwoven wicker, and when constructed to the dimensions proposed (about 16 feet square and 8 feet high) was found to be extremely efficient. It should be noted in reference to the great height (8 feet) of the Wild fence, that the normal rain gauge exposure in Russia was at least 1 metre, probably in many cases 1·5 metre, as a precaution against risk of burial in snowdrift, so that the angle at which driving rain would be intercepted was far smaller than if the gauge had been at the height of 1 foot. The

counterpart of the Wild fence which has been suggested by Dr. Mill for use in wind-swept districts in this country is therefore a turf wall 2 feet high, forming a ring about 6 feet wide, with the gauge in the centre.

Great as is undoubtedly the value of artificial wind protectors in ensuring the proper functioning of a rain gauge in exposed situations, it should always be borne in mind that natural shelter from wind is preferable. The ideal rain gauge exposure for wind-swept districts is one in which the prevailing wind is tempered by the interference of gently rising land or by a belt of trees. The angle of incidence of such shelter should not be greater than from 10° to 15° with the horizontal, varying with the degree of exposure to strong wind. If no such shelter is available, the gauge should be placed in a slight hollow, not of course a deep hole, so that it is protected from the direct impact of the wind. The gauge itself should always, if possible, be on level ground, and if in a hollow it should be at the bottom, not on the slope. If in the open, land sloping downwards towards the prevailing wind direction, even if at some distance, is detrimental. These precautions become less and less necessary with distance from the sea, except at hill-stations; and in sheltered valleys any additional specific shelter is usually unnecessary. In any circumstances, however, it is advisable to avoid sloping land for a gauge site, and even in fairly calm conditions a hillock or terrace makes a bad exposure.

Over-exposure of rain gauges is probably the most fruitful source of error in rainfall observing, and far too little attention has hitherto been paid to it in selecting sites for rainfall stations. It is extremely difficult to lay down any simple instruction which will entirely meet the case. A system of inspection

by officials thoroughly conversant with the varying requirements of each locality would do much to remedy the defect, but some time must elapse before any such scheme could be put into effective operation.

The opposite pole of danger in respect of faulty gauge exposure—viz. over-shelter—is much easier to avoid. Whilst it is true that a degree of shelter which would be harmful in one case would be much less so in another, broadly speaking, the conditions are similar everywhere. It is usually safe to suggest that the top of any object, such as a wall or other building, should never subtend an angle greater than 45° with the gauge. In windy positions, where the rain commonly falls at an acute angle, 30° is preferable to 45°. In the case of growing plants, shrubs, or trees, the angle should in no case be greater than 30°, that is to say, the distance of any such object should be at least twice its height. This allows for growth, which is apt to be overlooked as it takes place, and even when this precaution has been taken the encroachment of growing trees must never be lost sight of. It should be noted that whilst the error introduced by undue shelter by a wall or building is always caused by the interception of part of the rain, that caused by trees or shrubs may be either positive or negative, interception occurring under certain conditions, whilst at other times water-drops hanging on leaves may be blown into the gauge or drip from overhanging branches. In at least one instance in which a gauge was placed by a careless observer actually under trees, the positive and negative errors practically balanced, and, until the gauge was inspected, no fault in the exposure was suspected. This method of obtaining accurate records is not recommended !

CHAPTER V

MECHANICAL RAIN GAUGES

Self-registering rain gauges in great diversity have been introduced from time to time, but most of them have been short-lived and their defects, if any, have had little effect in putting erroneous readings on record. The automatic rain gauge has its proper uses, and is an important auxiliary to the direct-reading gauge when employed in the legitimate manner. It is necessary, however, to insist that in no respect can it be regarded as an instrument to relieve the observer of trouble; it should never be used entirely to take the place of an ordinary gauge, if only for the reason that no piece of mechanism, however perfect, can be expected to work with sufficient accuracy and uniformity in all circumstances when exposed to the vagaries of the British climate. It is therefore recommended that when a self-registering gauge is employed, and this is desirable whenever practicable, a gauge of the ordinary pattern should be set up alongside and used as a check upon its indications. The proper function of the self-registering rain gauge is to give a record of the time at which rain has fallen and of its duration and intensity, and for this to be done in a satisfactory manner certain precautions are necessary.

The types of automatic rain gauge which do not

supply these data and which are primarily intended for labour-saving devices are on this account to be regarded as objectionable. They have all the disadvantages of mechanical gauges without any of their advantages. The pattern most commonly met with is the dial gauge. In this instrument the rain, passing through the funnel, falls into a twin bucket balanced on a knife-edge and made to tip up and empty itself when filled to a certain weight, usually corresponding to ·01 inch. The other half of the bucket is then presented for filling, and in its turn tips up and empties, bringing the balance back to its former position. The movement of the bucket is made to turn an escapement wheel which actuates a pointer on a dial, so that the observer is able to read off the amount of rain which has fallen. In theory, there appears to be no great objection to the instrument, but any slight rusting of the parts or unequal wearing of the mechanism introduces an error so disproportionately large that after use for a year or two the indications of dial gauges are seldom to be trusted.

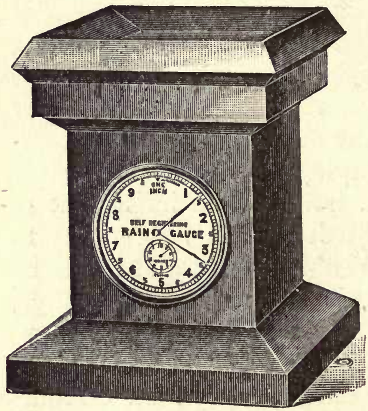


FIG. 35.—DIAL GAUGE.

A gauge depending on a somewhat similar device but so constructed that the movement of the buckets actuates a cam and by means of a lever raises a pen-arm and traces a line on a revolving drum has attained

a certain measure of popularity. This is enhanced in the view of some by the introduction of an electrical appliance whereby the recording part of the apparatus may be indoors. There is a certain fascination in watching the movements of a pen-arm tracing a line on a chart on a library table while the rain beats against the windows without, but this type of gauge can be regarded less as a scientific instrument than as an interesting toy.

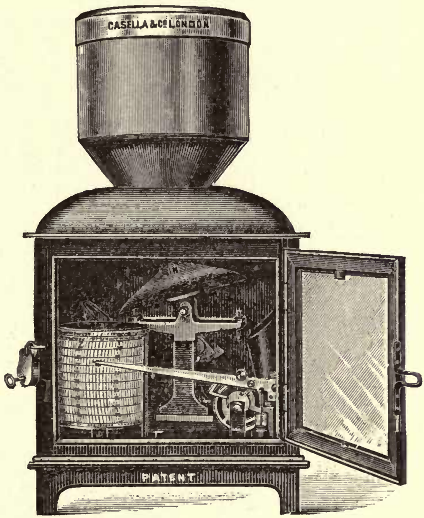


FIG. 36.—TIPPING BUCKET RECORDING GAUGE.

Besides suffering from the errors introduced by friction already mentioned, autographic tipping-bucket gauges recording by a pen-line fail to give a true record of the duration of light rain. The trace is, of course, in the form of a series of steps, each, as a rule, representing ·01 inch, and this amount is recorded without any indication of the time in which it was falling.

A considerable improvement on the tipping-bucket principle is that of the counterpoised bucket. In gauges of this kind, of which the "Casella Standard" is the most important

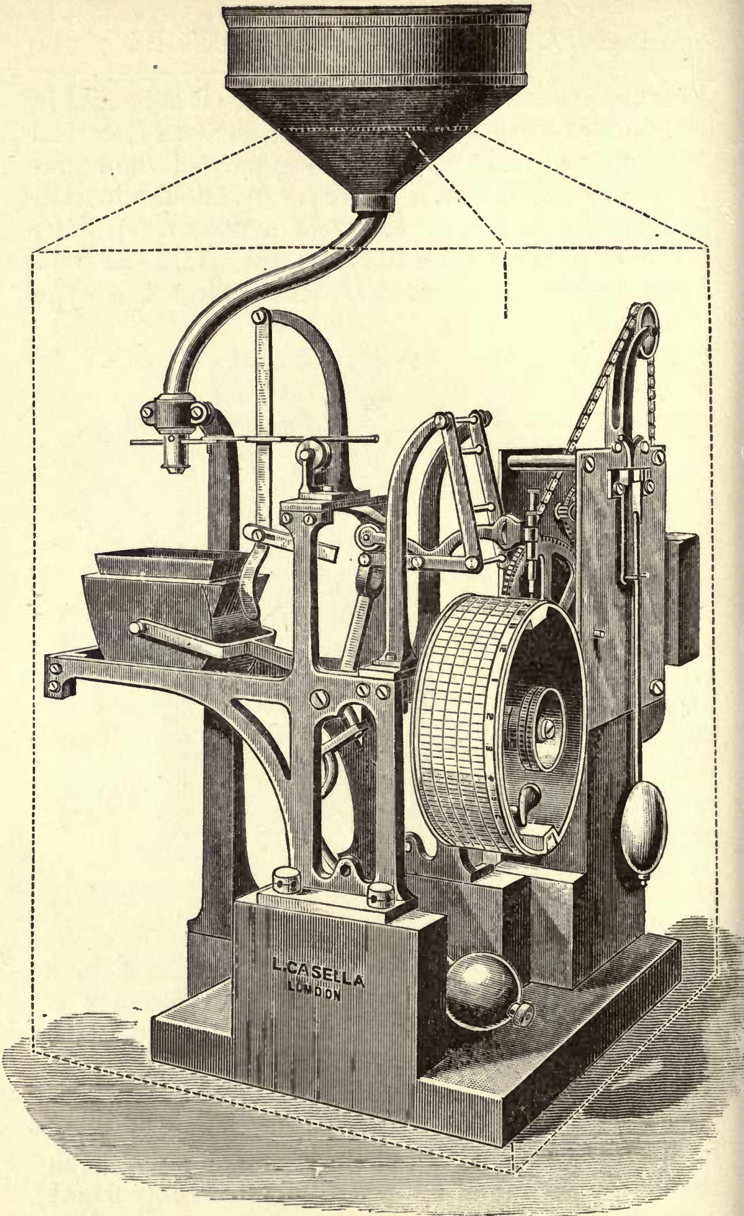


FIG. 37.—CASELLA STANDARD GAUGE.

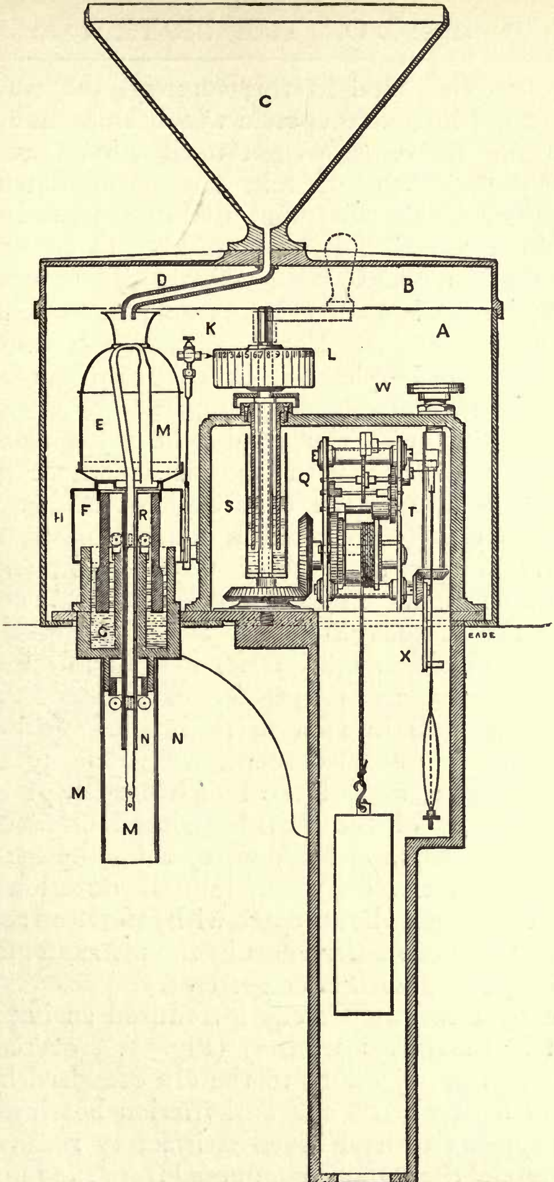


FIG. 38.—BECKLEY GAUGE.

representative used in this country, the water is conducted into a receptacle which sinks uniformly with the increased weight until a fixed amount, usually ·20 inch, of rain has accumulated. A simple device at this point overturns and empties the bucket, which is brought back to its original position by a counterpoise weight. The movement of the bucket is made to actuate a pen recording on a drum. The "Beckley" rain gauge is somewhat similar in principle, but in this case the bucket floats in mercury, and is emptied by a syphon. The objection to the tipping-bucket gauge, that friction interferes with the action, is of course applicable also to the counterpoised-bucket type; but the error introduced is much smaller, owing to the larger amount of water dealt with in each operation. There is no doubt, however, that both the Casella Standard and the Beckley are sluggish in action and inferior in light rain to more modern automatic gauges. It is of importance to appreciate this in view of the use of the Beckley gauge at the official observatories of the Meteorological Office, and of the long record kept at the headquarters of the British Rainfall Organization at Camden Square, London, by a Casella Standard gauge. Most records of rainfall duration kept before 1908 must be accepted with reserve on account of the want of sensitiveness in the instruments used in comparison with later patterns.

In 1911 Messrs. Casella introduced an improved model (Casella's Recorder) (Fig. 39), overcoming most of the objections to the old Standard by the use of lighter parts and anti-friction bearings, and this appears to have given satisfactory results. In this model the water is conducted from the funnel to

a balanced bucket, which is suspended from a two-armed pivoted lever and counterpoised by an adjustable balance-weight. As the bucket fills, it drops, and on reaching the lower end of a guide-plate turns over and empties itself, when the counterpoise weight causes it to return to its original position. The pen is attached to the end of the lever farther from the bucket, and is hung

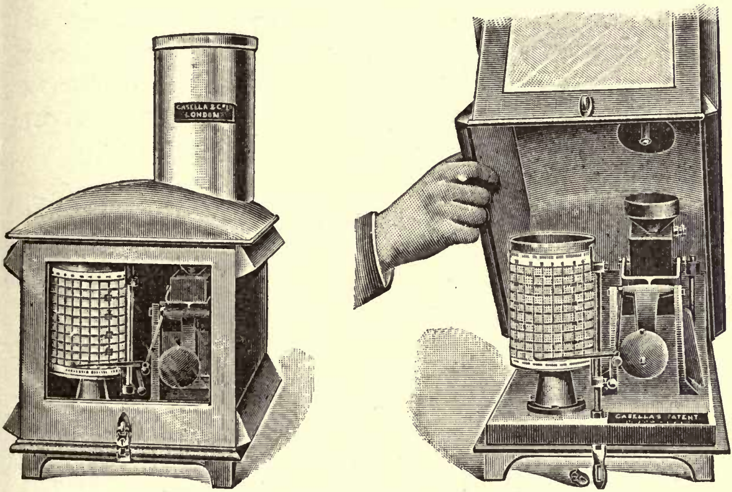


FIG. 39.—THE CASELLA IMPROVED RECORDER.

at right angles, being carried behind the revolving drum so that the time co-ordinates are rectangular.

A great step in the improvement of self-registering rain gauges was the re-adaptation of the float principle in Halliwell's Patent. The prime difficulty, which no previous design, save possibly Hellmann's gauge, had overcome, was that of bringing the float back to zero when the receiving chamber was full, a simple syphon being unsatisfactory for

many reasons. The Halliwell gauge, designed for use at the Fernley Observatory, Southport, for Mr. J. Baxendell, requires care in handling, and is not entirely free from minor defects, but in the hands of a conscientious observer who will not grudge a little trouble in keeping the working parts in order, it gives results of great accuracy.

The float system was also made use of in the "Hyetograph," also designed by Halliwell, on principles suggested by Dr. Mill. The descriptions of the mechanism of the Halliwell gauge and of the "Hyetograph" given in Dr. Mill's article in *British Rainfall*, 1908, are so clear that it seems best to reprint them.

"*The Halliwell Patent Recording Rain Gauge.*—This instrument gives the best and clearest trace of any I have tested. It is made to register on the drum seven days' rain or twenty-four hours' rain; and the latter form is the only one which I recommend, as the time-scale on any drum running for a week is too contracted for measuring the intensity of short falls.

"The large receiving funnel . . . . conducts the rain by a curved pipe to the bottom of the float-chamber, shown in the middle of the central diagram of Fig. 40. The float carries a rod, the top of which rests against the lower side of the pen-carriage (shown enlarged on the left-hand side of the diagram) and pushes this up, sliding between the rigid metal guides until the float-chamber is full and the pen has reached the top of the chart. The float-chamber is filled by half an inch of rain, and a side tube projecting on the right has hanging over it, on a delicately adjusted catch, a tube forming the short arm of a syphon, which branches above into an inverted U-tube, forming the long arm of the syphon (shown separately on the right-hand side of the central section in Fig. 40). As the lower part of the float-rod emerges above, on the float-chamber being filled, a triangular piece of brass attached to it throws over a small rocking weight, which detaches the suspended syphon, and this falls with the central short arm into the side tube of the float-chamber, starting the syphon full-bore, and emptying the chamber in five seconds. The float

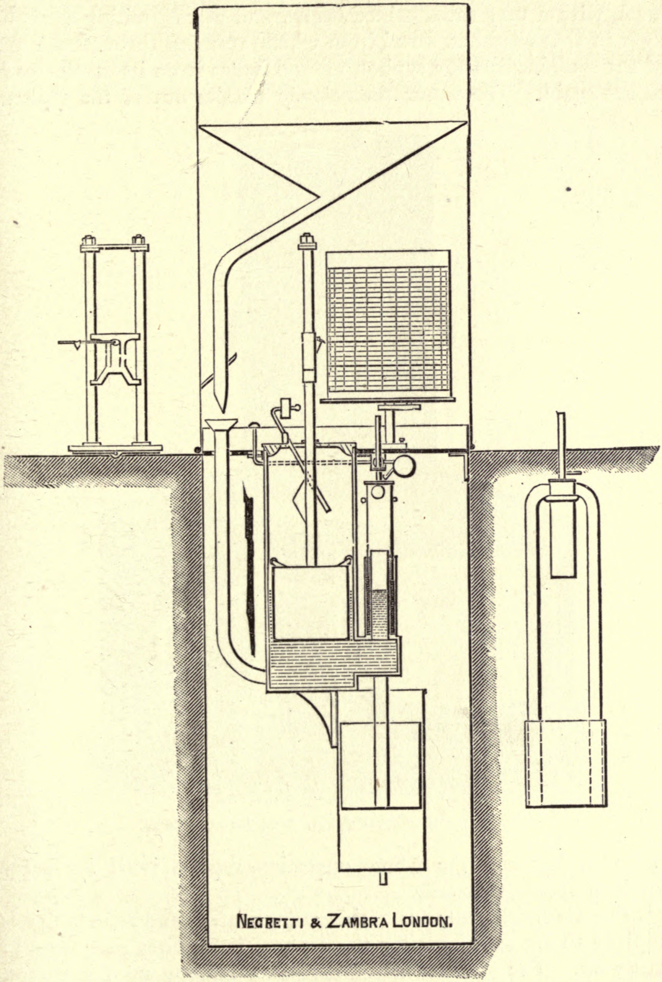


FIG. 40.—HALLIWELL GAUGE.

falls and the pen comes to zero on the chart. The water syphoned out of the float-chamber rushes into another chamber, at a lower level, with a very small orifice below, and fills it, raising a second float in that chamber, a rod from which, running through the axis of the syphon, lifts the syphon up and hangs it on its catch, ready to act again. The water then slowly trickles out of the syphon-

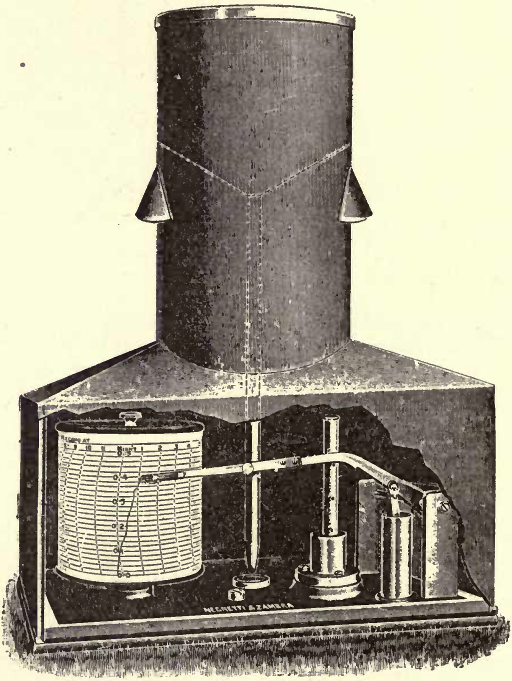


FIG. 41.—HYETOGRAPH, GENERAL VIEW.

float chamber and the whole operation repeats itself for every half-inch of rain that falls.

"The Halliwell gauge is rather complicated, and as mercury is required to act as a joint for the syphon, it requires some care in fitting up. The adjustment of the catch holding up the syphon is a delicate matter, as if it is too strong it may not be released, if too sensitive some accidental tremor may set it off before its time; but we are bound to say that as a rule it acts admirably."

"*The Hyetograph.*—The ordinary rainfall observer has neither the time nor the technical skill to tend a piece of delicate mechanism, nor does he care to spend as much as £17 on an instrument.[1] I had long thought over some way of cheapening the recording gauge by simplifying the mechanism without sacrificing the open scale usually given by frequent discharges of the water collected.

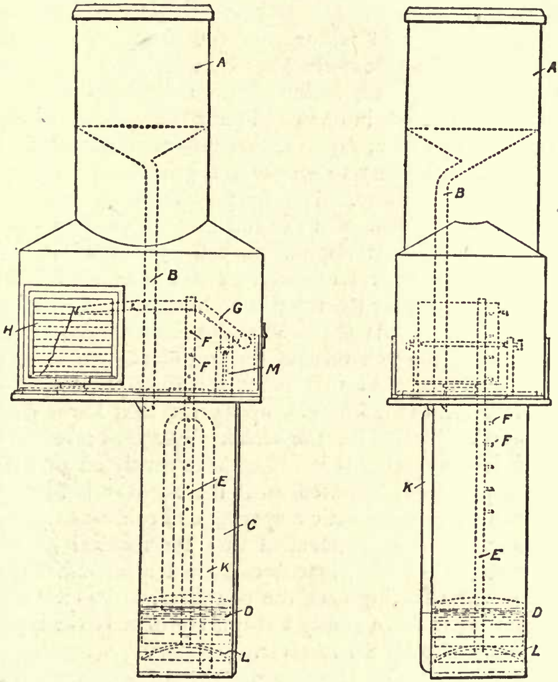


FIG. 42.—SECTIONS OF HYETOGRAPH.

I had thrown out the suggestion that the old type of rain gauge might be reverted to, in which the necessity of automatic emptying did not arise, the receiver being large enough to contain all the rain likely to fall in a day. I also suggested that the open scale might be secured by some arrangement by which the pen should drop automatically when it reached the top of the chart, while

[1] The pre-war cost of the Halliwell gauge.

the float-rod continued to rise. Mr. Marcus Zambra, of Messrs. Negretti & Zambra, was attracted by the idea, and his firm took the matter up, Mr. Halliwell working it out and patenting the instrument.

"A general view of the Hyetograph appears in Fig. 41, the lower portion, which is intended to be sunk in a drain-pipe or metal cylinder in the ground, not being shown. Fig. 42 gives two vertical sections of the whole instrument. It could not well be more simple. The rain falling into the funnel A is carried by the bent tube B to a float-chamber C, which is large enough to hold a little more than 4 inches of rain, an amount which is very rarely indeed exceeded in one day in any part of the British Isles. Of course, if more than, say, 2 inches were to fall any day before evening it would be easy to empty the gauge and leave it ready to record 4 inches more. The float D carries a rod E, which rises as the chamber fills. On this rod there is a row of projecting studs F, F, at equal intervals, and the pen-lever G, which is hinged at the right-hand end, rests lightly, by means of a side-plate, on the first of these studs with the pen at bottom of the chart when the gauge is empty. As the float rises the stud carries the lever up with it until the pen reaches the top of the chart, recording half an inch of rain. At that point the lever-plate slips off the stud and falls until it is brought up by the next lower stud with the pen at the bottom of the chart. The oil-brake M checks the fall of the lever so that it drops quite gently on to the lower stud. The process is repeated until the receiver is full. There is no mechanism for automatic emptying and consequently nothing to go wrong. It is recommended that the receiver be emptied every morning when the gauge is examined after rain has fallen. This is done by swinging back the pen-lever, lifting the float-rod a little, pressing it down gently but quickly to start the syphon K, which speedily empties the receiver.

"The merits of the Hyetograph are its extreme simplicity, the clearness and accuracy of its traces, and its low price: it is being offered at £6 15*s*. [pre-war price]. It has answered, in a satisfactory way, all the tests which I could devise, and the only drawbacks it possesses are, first, that the receiver is not large enough to hold 6 or 8 inches; but if it were, the float-rod would be unmanageably long; and second, that the pen describes the arc of a circle and not a vertical line as in the Halliwell or Casella gauges. This arises from the necessity of having an open scale, some of the magnification of the vertical rise being produced by

the lever, as to get it all either by increasing the diameter of the funnel or diminishing the diameter of the float-chamber would make the instrument more expensive or less efficient."

It should be mentioned that in the latest pattern of "Hyetograph" placed on the market by Messrs. Negretti and Zambra the pen-arm is carried beyond the drum, the pen being suspended at right-angles to it, as in the improved Casella Recorder, so that the time co-ordinate of the chart, instead of being curved, is rectilinear, thus satisfying one of the desiderata mentioned by Dr. Mill.

A modification of Halliwell's gauge doing away with its principal weak point, the mercury-joint, is the "Fernley" gauge, designed by Mr. Baxendell. The syphon in this instrument is secured against failure by a small feed-bucket, which automatically supplies it with a good flow of water at the moment of action and is itself refilled by the overflow.

The syphoning action of the Fernley gauge is an adaptation of the water-air-pump, the application of which to rain gauges is patented by Mr. Baxendell.

In the plan (Fig. 44), the main syphon tube, which is of very wide bore, is shown under letter D, and at the end of it is a trap E, to prevent air being sucked up into the syphon. A branch pipe F is attached to the syphon D, and leading into F is another pipe G, of smaller bore. The tilting bucket H is connected, by a rod J, with the tripping gear, which is actuated by the cam K when the float reaches its highest position. At this point the cam throws the weight over and the bucket is upturned. The water therefrom pours through the pipe G into the wider one F, creating a sufficient vacuum in the large syphon D fully to prime it, and thus quickly empty the reser-

voir A. In the course of syphoning, water is carried through a pipe M into the tilting bucket, which is thus refilled, ready for discharging on the next

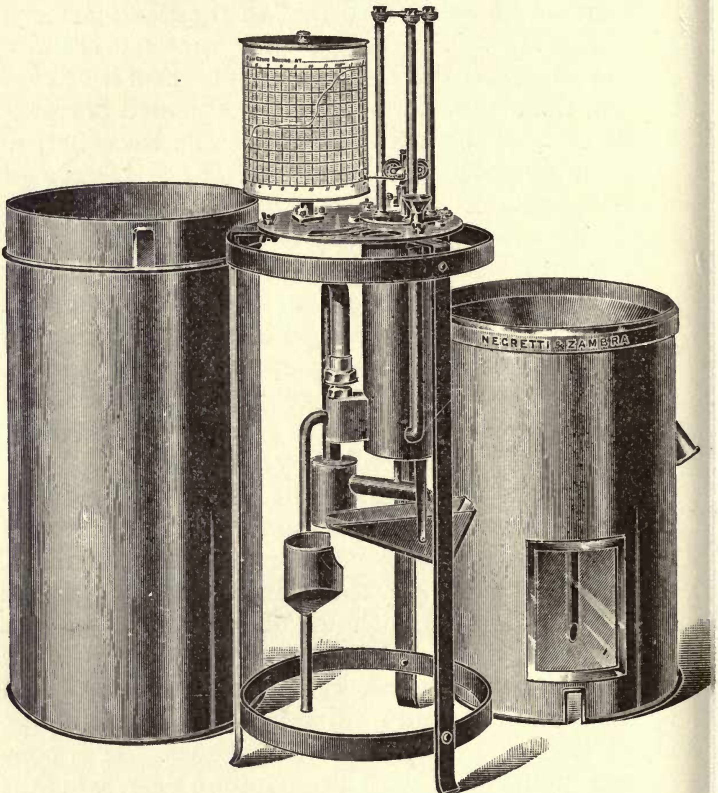


FIG. 43.—FERNLEY GAUGE.

occasion. There is, of course, a certain element of risk that in a long spell of dry weather the water in the bucket may evaporate. An additional improvement in the Fernley gauge is the pen-carrier.

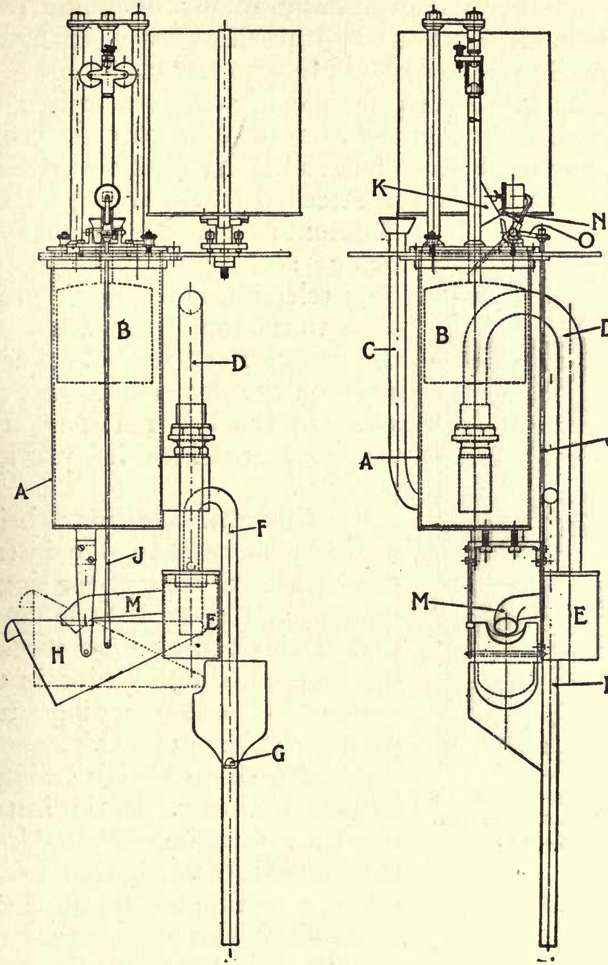


FIG. 44.—SECTIONS OF FERNLEY GAUGE.

Instead of the sliding arrangement of the Halliwell, which caused friction, or even stoppage, when dirty, the carrier consists of two anti-friction wheels, which

do not press continuously upon the guide rods. The guides are braced with a third rod in triangular form, in place of two only as in the Halliwell.

The Halliwell principle of weighted arm is retained, and when the cam turns it past its centre of gravity, this arm falls suddenly, the elbow striking the knob of the rod attached to the tilting bucket. A detent N keeps the weight from being accidentally overturned, only releasing it when the pen is close to the top of the chart. As the pen-carrier descends to zero, a pin on the descending float-rod automatically returns the weighted arm into its previous position.

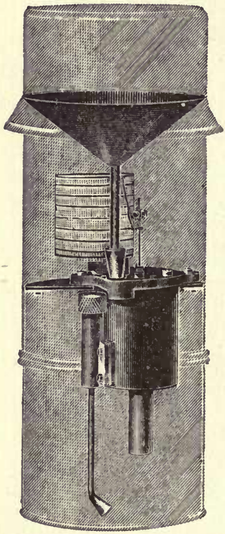


FIG. 45.—CASELLA'S SIMPLE SYPHON GAUGE.

Experiments are now being made by more than one instrument maker to readapt the simple syphon, and there is little doubt that if this can be done successfully a great simplification in the design of self-recording rain gauges will be obtained.

Fig. 45 shows Casella's Simple Syphon Recorder. In this instrument the water is conducted from the funnel into a float-chamber, in which the water-level, representing zero on the chart, is controlled by a capillary slot connecting the chamber with the syphon. As the water rises, the pen-arm attached to the float traces the record on the drum turned by a clock in the usual way. When the water-level reaches the point corresponding to ·50 inch on the chart, the syphon-tube

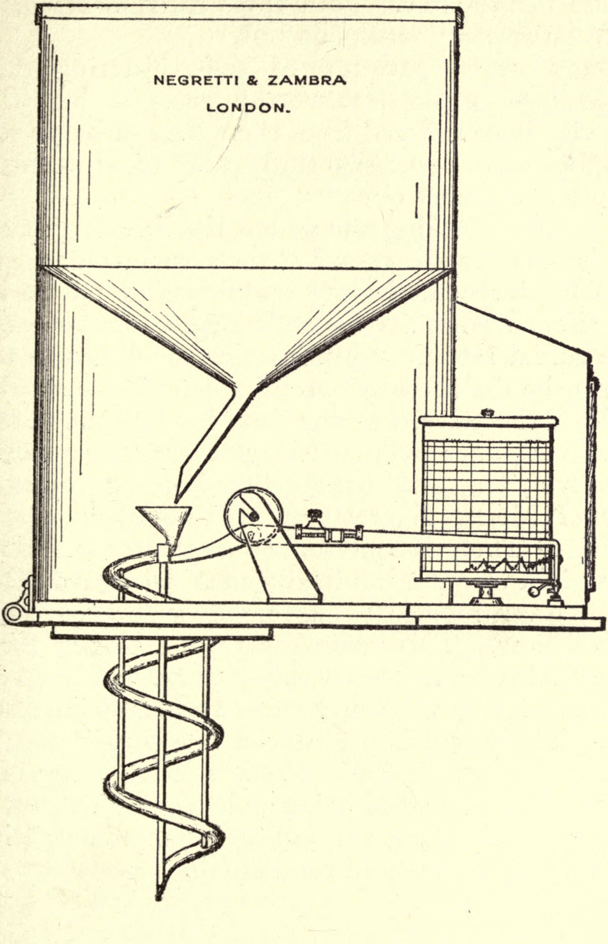


FIG. 46.—NEGRETTI & ZAMBRA'S RAINFALL RATE-RECORDER.

discharges it. A capillary neck at the top of the syphon ensures freedom from dribbling over. Messrs. Negretti and Zambra's syphon gauge is

similar in principle. Both these instruments have given satisfactory results on test.

Many other patterns of self-registering rain gauge have given trustworthy records, but the majority have suffered from the defect of being too complicated or too easily thrown out of adjustment for use in ordinary circumstances.

The self-recording rain gauge, if sufficiently sensitive, gives a graphic record of the actual incidence of rainfall which enables the mean rate of fall to be determined with a reasonable degree of accuracy. The actual rate at any particular moment can, of course, be deduced by careful measurement of the angle of the trace, but the need has long been felt of an instrument which will give this information directly. This need has recently been met by another of Messrs Negretti and Zambra's ingenious devices. The principle adopted is that of recording the weight of water passing down an inclined surface at any given moment, the weight varying with the rate of flow. This inclined surface takes the form of a spiral tube, delicately suspended at one end of a balanced lever, the other end of which carries the pen. The graph is made on a revolving drum in the same way as in an ordinary self-recording rain gauge; but instead of being an integrating curve, it is differential, rising and falling in accordance with the varying intensity of the rainfall.

CHAPTER VI

THE MEASUREMENT OF RAINFALL DURATION

It is desirable, whenever possible, to obtain accurate measurements of the duration of rainfall as a supplement to records of its amount. Until some information of this kind became available, our ideas of rainfall duration were dependent upon rough, non-instrumental estimates, which, even if they rose above mere guesswork, could hardly be regarded as scientific observations.

In this country both Mr. Symons and Mr. Gaster referred to the desirability of obtaining records in the early sixties, but apparently no attempt to deal with the matter was made till 1869, when Mr. F. E. Sawyer brought together a few records of duration made at Brighton and at Bogside in Aberdeenshire.[1] He remarks that duration of rainfall had previously been recorded in Canada. There appears to be no doubt, however, that both Mr. Sawyer's records and those referred to as made in Canada were non-instrumental. All other early references to so-called rainfall duration appear to be based merely upon frequency values deduced from hourly observations. A great deal of ingenuity was expended during the latter half of the nineteenth century in devising various forms of automatic rain gauges, and it is curious to find that their records were apparently not used for

[1] See *British Rainfall*, 1869, p. 10; 1870, p. 35; 1871, p. 42.

this elementary purpose. In 1880, however, Mr. Baldwin Latham published in *British Rainfall* a series of records of measured duration at Croydon, which rank as the earliest observations in any way comparable with modern duration records. These records were subsequently continued without a break to 1916. Beyond this no data appear to have been published for about twenty years, when the records of a self-recording rain gauge established at Seathwaite in 1899 by Mr. Symons were discussed in a paper by Dr. H. R. Mill read to the British Association at Southport in 1903. A second paper on the same subject was read before the Royal Meteorological Society in April 1905.[1]

In 1904 Dr. Mill made an analysis of the traces from the Casella Standard gauge at Camden Square from 1881 to 1904, and published the results *in extenso* in *British Rainfall*, 1904. In the volume for the previous year a section was devoted for the first time to records of measured duration, four sets of observations from the south of England being published. The number of records received grew very slowly, and five years later *British Rainfall*, 1908, contained only ten, but the introduction of less expensive self-registering rain gauges after this date provided a stimulus, and in *British Rainfall*, 1919, the number had grown to 60 records.

In all the types of self-registering rain gauge employed for measuring rainfall duration the record is traced on a drum by an integrating curve which indicates the intensity of the rainfall by its inclination to the horizontal lines on the chart. When rain is not falling, the pen travels parallel to the base line. In order to obtain a measurement of the duration

[1] See *Q.J.R. Met. Soc.*, vol. xxxi, 1905, p. 229.

of rainfall for the period covered by the chart, it is necessary to measure the periods during which the trace is not parallel to the base line. In practice it is found to be convenient to lay a ruler along the bottom of the chart and rule a line covering only those periods when rain is seen to have been falling; the portions of this discontinuous line are subsequently collected and measured in terms of the time-scale of the chart, the result being expressed in hours and tenths of an hour. After long practice the computer usually finds it possible to dispense with

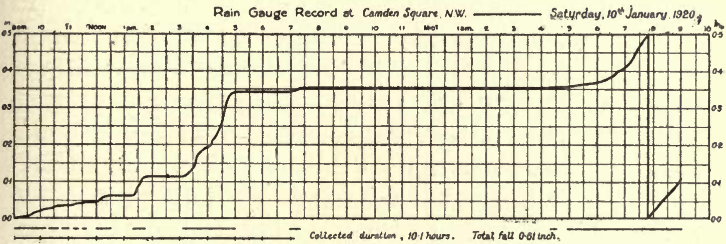


FIG. 47.—MEASUREMENT OF RAINFALL DURATION FROM CHART.

the ruling and measure the duration by eye, but this is not recommended at first.

In order to get results of any value, the drum of the gauge should make a complete revolution every twenty-four hours; in gauges with drums revolving only once in a week the scale is too restricted for accurate measurement. It is also important that the trace should be a continuous line. Gauges of the "step-by-step" type, recording each ·01 inch or ·005 inch by a separate vertical movement of the pen, give good enough records when rain is falling heavily and continuously, but give no indication of

the true duration during very light rain. In placing the chart on the drum of any self-registering gauge great care must be taken to set it perfectly straight; otherwise the pen will trace a line at a slight inclination to the base line when no rain is falling, and even if rain is falling the degree of the inclination will be affected. It is a good plan to set the pen at the bottom of the chart and make a complete revolution of the drum by hand, thus drawing a fixed base-line by which the accuracy of the setting may be tested. A fixed zero-pen was at one time tried at Camden Square, but this was not found satisfactory.

It must be remembered that no self-recording rain gauge will work well and consistently without constant care and attention. Any friction in the working parts may cause it to give seriously erroneous results. As an example of this, in gauges of the float type, where the pen is actuated by the movement of a float which rises as the rain enters the receiver, should there be any tendency for the float-guides to jam, the pen shows no vertical movement till the pressure of the water becomes great enough to overcome the resistance, and when this happens it rises with a jerk, so that the slow and steady rain of an hour may be recorded as if it had fallen in a minute. In the record of the amount of rain registered this causes no error, but in the record of duration the error is liable to be large. Proper lubrication of all working parts prevents this type of failure.

With regard to proper lubrication, Mr. F. L. Halliwell advises that, bearing in mind that friction depends largely on pressure between moving parts, where pressure is very slight, a dry, well-polished

surface or one burnished with dry graphite gives less retarding effect than can be obtained by the application of a fluid lubricant, as the viscosity and capillary action may prove more retarding than friction. Where pressure is considerable, the application of light oil of good lubricating quality, if not allowed to become dirty or gummy, is generally advisable. Applying these principles to the Hyetograph, the following points may be mentioned :

(1) The guides on the float are always wet and pressure on them light, so that fair working conditions prevail. (2) The float spindle guide being of considerable area, and pressure slight, a well-polished rod and guide or one burnished with graphite provides less retarding effect than oil. (3) The pen-lever plate which rests on the float spindle pegs, and also the pivots of the pen-lever, are preferably lubricated with clock oil, frequently cleaned off and renewed, since here the pressure is considerable. (4) The pen-pressure on the chart should be as light as possible consistent with reliable contact.

In order that there may be no break in the record during snow, some means must be introduced to melt the snow as it falls so that it shall not accumulate in the funnel of the gauge. In some gauges a small paraffin lamp is used, but a night-light is usually sufficient and is less liable to overheat the gauge and give rise to evaporation.

It is strongly recommended that an ordinary direct-reading rain gauge should always be placed alongside a self-registering gauge as a check, and if the two show any appreciable difference in the amount recorded, the latter should be overhauled. Faulty recording usually arises from unequal wearing of

some part of the mechanism, or from clogging due to dust adhering to dried oil.

In case of any temporary failure or partial failure of the gauge, the duration should be interpolated as far as possible by eye observation, and it is therefore advisable to compute durations day by day rather than to allow the charts to accumulate till the end of the month or year, when the particular circumstances may have been forgotten. Another advantage of daily measurement is that it reduces to a minimum the risk of mistaking accidental irregularities in the trace for records of rainfall.

Given a suitable self-recording rain gauge, properly handled, it is a simple matter to measure the duration during heavy or moderately heavy rain. With very light rain, however, and it must be remembered that from the point of view of duration the very light rain forms a large fraction of the whole, the element of personal equation comes into play. Observers are asked to include in the duration total all periods when the curve is perceptibly rising; but what is perceptible to one person may be imperceptible to another, and there is no doubt that some of the inconsistencies observed in duration records can be attributed to this cause. A close analogy occurs in the measurement of the duration of sunshine, but the discrepancies are probably larger in the case of rainfall duration.

The personal element is, however, not the sole source of trouble. The improvements which have been introduced in self-registering rain gauges in the last few years have nearly all tended towards producing an instrument of higher sensitiveness, so that if one compares, for example, the traces of the old Casella Standard with those of Baxendell's

"Fernley" or improved Halliwell gauge, it is obvious at once that whilst the Fernley is capable of recording rain hardly more intense than a Scotch mist, the older gauge requires distinctly heavier rain to set it in motion. To take an extreme instance, therefore, it is quite possible to have the case of a day when precipitation is quite perceptible for many hours, but so light that it produces only a few drops in the rain gauge. In such circumstances the Fernley may show a slow gradual rise of the curve, quite distinguishable on its very open-scale chart, and a duration of ten or twelve hours, whilst the less sensitive gauge records a day of no rain. If the duration is measured in one case as 12 hours and in the other as 0, we have the elements of a discrepancy of the first magnitude. Even so apparently trivial a matter as the degree of fineness of the pen-line may affect the apparent duration considerably in this type of weather, and there was a distinct increase in the duration values recorded at Camden Square when the Casella Standard was fitted with a pen instead of the original pencil.

There are not many data upon which to base a comparison between the results from different types of self-registering rain gauge, because for this purpose it is necessary that two or more gauges should have been maintained side by side for a considerable period and the curves measured by the same computer. In a paper read before the Royal Meteorological Society in 1916[1] an attempt was made to examine this question by means of two short series of parallel records with a Halliwell gauge and a Hyetograph observed respectively at Thirsk by Mr. A. J. Walker and at Aberclyd, in Brecon, by Mr. J. R. Gethin Jones. In both cases it was

[1] See *Q.J.R. Met. Soc.*, vol. xliii, 1917, pp. 29.

found that the duration of rainfall measured by the Halliwell exceeded that by the Hyetograph by about 10 per cent. The durations for the two gauges agreed more closely in summer than in winter, a result, no doubt, due to the greater prevalence of rainfall of very slight intensity in winter. It is not impossible that some of the disparity may have arisen from unequal loss by evaporation in the two gauges. The Halliwell is certainly much more air-tight than the Hyetograph, and the air-space within the cover is considerably smaller. Mr. Halliwell suggests that the discrepancy may be due to the difference in the ratio between the area of the orifice and of the wetted surface inside the funnel. In the Hyetograph with a 6-inch funnel this is about 1 : 5, and in the Halliwell with a funnel 11 inches in diameter about 3 : 10.

An examination of the records from various stations, taken with four different patterns of gauge, suggests that the Casella Recorder (not the Casella Standard) gives relatively the highest duration-values and the Beckley the lowest, whilst the Halliwell and the Hyetograph are intermediate. This gives a rough indication of the comparative sensitiveness of the gauges, although it does not provide any means of standardization. It sounds a note of warning against accepting duration-values without paying great attention to the pattern of gauge from which they were obtained.

The problem of standardizing rainfall duration records is one of peculiar difficulty. A solution might be found either in insisting on a standard instrument or in a modification of the method of measuring the traces. If the latter course is adopted, it is clear that since one gauge will register

in very light rain, whilst another will not do so, one must either leave the very light rain out of account altogether or place it in a different category. A great many very tedious experiments would be necessary in order to hit upon a suitable minimum intensity below which the duration of rain should be excluded. If this is put too low, it will fail in its object; if too high, there is a risk of getting a false impression of the prevalence of very light rainfall and its geographical distribution. A test analysis has been made of the Halliwell and Hyetograph traces recorded at Thirsk in 1915, measuring the total visible duration and, separately, the duration exceeding the rate of ·01 inch in three hours (0·1 mm. per hour). This limit was selected as likely to be perceptible in almost any kind of gauge, and yet a rate below which rainfall is not of any practical importance. The results showed that, although on the whole year the records from the two gauges are brought slightly more into accord, during part of the period the disparity is even increased by omitting the very light rain. On the whole year the measured duration was reduced by 11 per cent. for the Halliwell and by 9 per cent. for the Hyetograph. This appears to indicate that the limit tentatively selected was too low to eliminate the original discrepancy between the results for the two gauges. There is, however, reason to think that the adoption of a minimum rate considerably reduces the discrepancies in measurement brought about by personal equation, and largely for this reason it is probable that the method will have to be accepted as a *pis aller*. For official duration records the minimum of 0·1 mm. per hour, or about ·005 inch per hour, is therefore being recommended.

CHAPTER VII

THE MAPPING OF RAINFALL DATA

THE cartographical treatment of rainfall observations has been developed in this country in a remarkable manner by Dr. H. R. Mill. The advantages which arise from this method of treatment are many. It affords a valuable means of detecting errors in the records, whether arising from defects in the gauge or its exposure, or from mere mistakes in making the measurements, entering them, or adding them up. In order that the fullest opportunity may be given for effecting this detective process, it is desirable that the observing stations shall be numerous, and that the observations shall be synchronous. Thanks to Mr. Symons's unremitting efforts to attain these objects, there exists at the present time an observing corps about 5,000 strong, operating on a nearly uniform plan. As far as practicable, observations are made once daily at 9 a.m. (Greenwich time), the rule being that the amount measured on each morning should be entered in the register against the date of the previous day. Measurement at any other hour renders the readings out of harmony with others, and, since intercomparability is essential, robs the records of much of their value. Since the introduction of "summer time" in 1916 the high level of uniformity in this respect which had been laboriously attained has

been somewhat marred. Failure to comply with the rule as to date of entry not only throws the daily readings into confusion, but affects the monthly and annual totals to the extent of one day's rainfall, the amount which should properly be entered to the last day of any month being credited to the first day of the succeeding month. In order that the readings of gauges measured once monthly should be in accord with those read daily, the time of observation recommended is 9 a.m. on the first of the month, and with a weekly gauge an additional measurement at that hour and day achieves the same purpose.

The extent to which the cartographical treatment of rainfall records can be utilized as a means of detecting and evaluating errors depends upon a variety of circumstances. In the case of systematic errors, such, for example, as would arise from the employment of a measuring glass graduated for a gauge of different diameter to that in use, a repeated discordance with the records at surrounding stations in each of several maps soon becomes apparent. The error in this case would take the form of a difference from uniformity more or less proportional to the amount of the falls dealt with. A somewhat similar case would be an error caused by a leaky gauge, but the discordance would be less regular in its incidence. A mere arithmetical mistake or mistranscription, on the other hand, would, of course, affect only the map in which the individual misreading occurred, and would not obtain any support from other maps except in cases where, through carelessness on the part of the observer or copyist, mistakes of the same kind occurred repeatedly. Such errors would, of course, be occasional and of varying magnitude. Errors in observations arising from faulty exposures would,

unless very flagrant, be observed only in dealing with periods in which the type of weather experienced was such as to affect the measurements sufficiently for detection. Faulty recording of snowfall would be a case in point. Similarly with gauges over-exposed to wind, in accordance with the hypothesis discussed in Chapter IV, large errors would, as a rule, appear only when windy weather, or in specific cases wind from certain quarters, had been experienced.

One of the greatest difficulties in detecting errors in rainfall records—and this applies with most force to errors due to over-exposure—lies in the fact that in any individual reading the amount of the error is usually smaller than the difference from the reading at a neighbouring station which may arise naturally. A systematic error becomes more apparent when the totals for a considerable period are compared, but even then it is apt to be mistaken for a geographical variation.

The range of variation which can be safely overlooked as fortuitous diminishes with increase of period. In thunderstorms cases are known to have occurred in which several inches of rain have fallen at one station whilst less than a mile distant no rain has fallen. In a single month's fall a variation of, say, 25 per cent. might be due to some local thunderstorm, and in a month when thunderstorms are known to have occurred it would not be safe to assume that an even larger variation was due to error. In a map of the rainfall of a year a variation of 10 per cent., not explained by the configuration, should give rise to suspicion, and in the case of a map of average rainfall for thirty or forty years, a 5 per cent. variation would almost certainly indicate error. In

a large number of cases records showing want of harmony in this way have been made the subject of special investigation. In practically every instance the gauge has been found to be faulty, either in construction or exposure in one of the ways described. It is true that a very small number of cases of persistent variation remain unexplained, and that the subject is far from fully investigated, but a body of experience gained during about twenty years devoted to the subject gives confidence in the expression of the general opinion that the systematic mapping of rainfall data provides the surest safeguard against the employment of erronous records from whatever cause the errors may arise.

The day of twenty-four hours being taken as the time-unit of rainfall measurement adhered to by the great majority of observers, any period which is a multiple of the "rainfall day" may be made the subject of cartographical study. For some purposes it would undoubtedly be an advantage if uniform observations covering shorter periods than one day could be mapped; but until there is a much wider use of self-recording rain gauges than at present, this will not be practicable.

The method of studying synchronous observations by mapping derives its great value from the vitality which it imparts to the data. Lists of figures fail to convey, even to the most imaginative mind, any sense of the reality of the facts which they embody. It is extremely difficult as a rule to grasp simultaneously the import of a mass of statistics, even though arranged in the most orderly sequence which it is possible to devise. But the same data written on a map, each over the site of the place at which the observation was made, appeal immediately

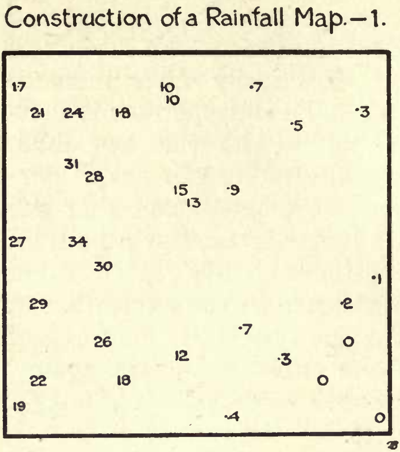


FIG. 48.—PLOTS OF RAINFALL IN TENTHS OF AN INCH.

to the mind, through the eye, by standing each in its correct relation to the others. The force of this reconstructive process is increased if, in addition to plotting the readings, the regional distribution which they indicate is emphasized by the addition of lines passing through points on the map at which the values are equal. Thus, as in Fig. 48, if a number of measurements of rainfall on, say, an individual day are plotted, lines representing the values zero, ·50 inch, 1·00 inch, 2·00 inch, and 3·00 inch, for example, may be drawn, and by this means a picture of the rainfall distribution is arrived at (Fig. 49). A further step in emphasis is made by tinting the zones between successive lines with distinctive

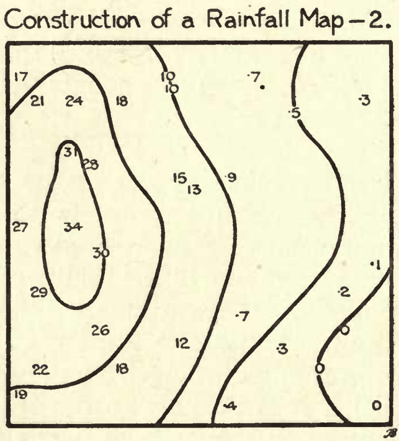


FIG. 49.—ISOHYETAL LINES.

shading (Fig. 50). At this stage the original observations may be dropped altogether, and the statement of the day's rainfall observations remains in the form of a map, at the same time more pleasing and more instructive than the bare figures from which it was built up. The process is not entirely wanting in analogy with that of reconstructing the body of an animal, as it appeared in its lifetime, from a heap of unattractive-looking bones and a few fossilized footprints, but the force of the analogy lies less in the exercise of the imagination than in the employment of deductive reasoning.

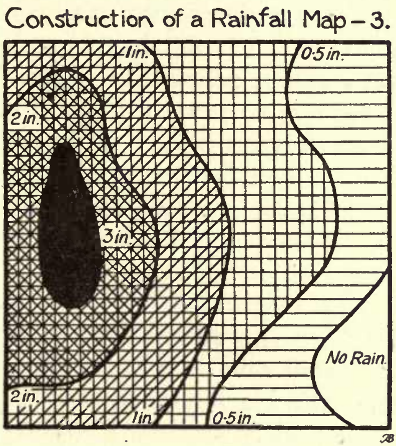


FIG. 50.—ZONES OF RAINFALL.

The lines drawn on a rainfall map, when they represent the distribution of the amount of rainfall in some specified period, are known as Isohyetal lines, or Isohyets. They are precisely similar in principle to contour lines representing elevation, and form the readiest and simplest means of expressing values in three-dimensional space on a plane surface. Isohyets differ from Isobars, or lines of equal barometric pressure, and Isotherms, or lines of equal temperature, as commonly used by the meteorologist, in that they represent the actual measurement made, not a derivative thereof, as in the case of data which require to be reduced to hypothetical

sea-level values before their true significance can be grasped.

Rainfall maps are not necessarily strictly "isohyetal." They may, for instance, represent the frequency of occurrence of some phenomenon, such as the number of days in a month or a year on which some specific amount of rain has fallen; or, again, they may represent the relative period, at various places, of some phenomenon of varying duration, as a drought; or the relative intensity, such as the mean rate of rainfall per hour in different parts of the country. Yet another example of rainfall mapping is that which represents the data not absolutely but relatively to some other set of data, usually to the average values over a number of years. A map constructed on these lines is in effect an expression of the relation of two maps to one another. Examples of all these kinds of rainfall map will be referred to more particularly in later chapters.

Experience in the construction of rainfall maps leads to the recognition of certain recurring types of distribution, in some cases definitely related to the distribution of other physical phenomena, in others with well-marked seasonal variations. It is the identification of these types and correlations which points the way to the laws underlying the control of rainfall by other factors, as, for example, the movements of low atmospheric pressure centres, or the general atmospheric circulation and the configuration of the land.

A further consideration of some importance in connection with the cartographical treatment of data is the facility which it gives for the accurate weighting of individual observations in arriving at *general* values applicable to areas. The general

rainfall value for any area, as defined by Dr. Mill, is the mean of an indefinitely large number of values for points equidistantly spaced over the area in question, so that whatever may be the distribution of the fall, the resultant applies to the area as a whole. Thus, if over an individual 100 square miles of country the *volume* of rain which falls in any particular period amounts to 100 sq. miles × 1 inch, though it may have been the case that 3 inches fell in one spot and nothing at all in another, the general rainfall for the 100 square miles under the definition would be 1 inch. In all volumetric computations based upon rainfall records such general values are of great practical importance. At first glance the natural method of arriving at the general rainfall for any area for any specified time appears to be to take the arithmetical mean of all the observations available for stations within that area. If by any chance it happened that the stations for which readings were available were sufficiently numerous and so situated as to be equidistantly spaced over the area, this method would yield an approximately correct result, but this is rarely the case. In some instances, if there are sufficient stations, the accuracy of a general value arrived at by this method may be improved by weeding out some of the readings in the part of the area where they are numerous and thus equalizing the representation by reducing it to the density of the worst provided portion. Where any appreciable part of the area is entirely devoid of records, this expedient fails entirely, and at best it depends very largely upon the chance possibility of arriving at a well-balanced selection.

As is made clear in Fig. 50, by the cartometric method the distribution of rainfall is indicated by

lines dividing the area under observation into a number of zones within each of which the amount of the fall varies only between the limiting values expressed by the lines. The lines may be drawn at any convenient intervals, thus limiting the variation within each zone to any desired extent. As a result it becomes an extremely simple matter to estimate the general rainfall of each individual zone, this, as a rule, being the mean between the two limiting values. The only difficulty arises in the case of zones with but one limiting value expressed by a line, such as enclosed dry or wet areas, or zones adjacent to the outside boundary of the area under consideration, but even here a little practice enables a reasonably accurate estimate to be made. In order to combine the general values for the zones and obtain a single general value for the whole area the size of each zone must be determined. This can be done either by ruling up the map with a network of small equal squares and counting the number of squares in each zone or, better, by means of a planimeter. Multiplying the general rainfall of each zone by its area, we get the volume of the fall, and by adding together the volumes for all the zones the volume for the whole is obtained. If this total volume be divided by the total area the general rainfall applicable to the whole is arrived at. Examples of the application of this method will be found in later chapters.

Another method by which general values may be deduced from rainfall observations which have been expressed in cartographic form is sometimes found more convenient. After drawing the isohyets, the map should be ruled in equal squares; the finer the network of squares the more accurate will the final

result be. At each of the points of intersection of the lines forming the squares a value should be interpolated, based upon the rainfall distribution indicated by the isohyets. The arithmetical mean of all the values so interpolated will give approximately the same result as the planimetric method. In work of great precision it is sometimes desirable to proceed by both these methods, each of which forms a check on the other.

The application of cartography to rainfall observations does not stop short at the mere restatement of the data in a form different from, and more readily manipulated than, tabulation. When the type of distribution dealt with is fully recognized, it becomes possible not only to represent the observed data by means of isohyets, but to exterpolate values with considerable confidence in districts where no observations are available. This is especially the case when the period dealt with is sufficiently long to enable the distribution to be definitely related to the configuration of the land. Thus, in constructing maps of average rainfall in which the dependence of the amount of the fall on the land surface in conjunction with the observed prevailing winds is known, the lines may be drawn over the bare spaces of the map by analogy with similarly situated districts where actual observations are available. Proof of the accuracy of the reasoning on which this method of exterpolation is based is provided when, after the construction of a map in the way described, fresh observations have come to light in places hitherto unrepresented. In a fully considered rainfall map such records are found to fit into their places on the map remarkably well.

It is obvious that rainfall observations cannot be

made everywhere, and since in the construction of a rainfall map the compiler must commit himself to an expression of opinion as to the true rainfall in every part of it, approximate accuracy is far more likely to be attained if the lines are drawn in the way which is the most probable. In the present state of our knowledge, save for certain broad principles which will be laid down later, no infallible rules for correct rainfall mapping can be formulated, and experience gained by constant practice is still the surest guide.

CHAPTER VIII

THE INCIDENCE OF DAILY RAINFALL

As has already been mentioned, the number of stations for which tabulated data exist for any period of time less than the "rainfall day" of twenty-four hours from 9 a.m. to 9 a.m. is too small to give a basis for studying regional distributions by cartographical methods. A certain amount of information is, however, available, and it is in some respects of considerable interest.

THE DIURNAL RANGE OF RAINFALL

Self-recording rain gauges of the Beckley pattern have been in use continuously at four First Order Observatories of the Meteorological Office, at Aberdeen, Valentia (Kerry), Kew, and Falmouth, since 1871, and average values for the 45 years 1871-1915 give the amount of rainfall during each hour of the day. The period is not long enough to ensure that the irregularities due to abnormal rains are smoothed out, but the results are nevertheless suggestive. The table on p. 106 gives the values for January and July, illustrating the difference between summer and winter. It will be seen that both in January and July there is slightly more rain in the night than in the day at Valentia, the only station of the four at which the rainfall is preponderatingly of the "south-westerly" type. At the

AVERAGE RAINFALL IN EACH HOUR OF THE DAY

Hou.	January.				July.			
	Aberdeen.	Valentia.	Kew.	Falmouth.	Aberdeen.	Valentia.	Kew.	Falmouth.
	in.	in.	in.	in.	in.	in.	in.	in.
a.m.								
0.30— 1.30 .	·002	·009	·002	·006	·003	·006	·002	·004
1.30— 2.30 .	·003	·008	·002	·007	·003	·006	·003	·004
2.30— 3.30 .	·003	·009	·003	·006	·003	·006	·003	·006
3.30— 4.30 .	·003	·008	·003	·007	·004	·006	·002	·005
4.30— 5.30 .	·003	·008	·003	·006	·004	·006	·002	·005
5.30— 6.30 .	·004	·007	·002	·006	·003	·007	·002	·005
6.30— 7.30 .	·004	·008	·002	·007	·003	·007	·003	·004
7.30— 8.30 .	·004	·008	·003	·006	·003	·007	·002	·004
8.30— 9.30 .	·004	·009	·003	·006	·003	·006	·002	·004
9.30—10.30 .	·003	·007	·002	·006	·003	·005	·002	·004
10.30—11.30 .	·002	·006	·002	·005	·003	·004	·003	·002
11.30—12.30 .	·003	·007	·002	·006	·005	·004	·004	·004
p.m.								
12.30— 1.30 .	·003	·007	·002	·006	·005	·004	·005	·004
1.30— 2.30 .	·002	·008	·002	·007	·006	·004	·004	·005
2.30— 3.30 .	·002	·008	·003	·006	·006	·004	·005	·005
3.30— 4.30 .	·003	·006	·002	·006	·006	·004	·004	·004
4.30— 5.30 .	·002	·007	·003	·007	·005	·005	·003	·004
5.30— 6.30 .	·003	·008	·003	·006	·005	·005	·004	·003
6.30— 7.30 .	·003	·007	·003	·006	·004	·005	·004	·004
7.30— 8.30 .	·003	·008	·002	·006	·004	·005	·004	·004
8.30— 9.30 .	·003	·009	·002	·006	·003	·004	·003	·003
9.30—10.30 .	·002	·009	·002	·007	·004	·005	·003	·004
10.30—11.30 .	·003	·008	·002	·006	·003	·005	·003	·004
11.30— 0.30 .	·003	·009	·002	·007	·004	·006	·003	·004
Total for day .	·070	·188	·057	·151	·095	·126	·075	·099
Day from 6.30 a.m. to 6.30 p.m. .	·035	·089	·029	·075	·053	·059	·041	·047
Night from 6.30 p.m. to 6.30 a.m. . .	·035	·099	·028	·076	·042	·067	·034	·052

other stations there is no apparent difference between the day and night rainfall in winter; but in summer at Aberdeen and Kew there is a well-marked maximum in the day, culminating at about 3 p.m. These two stations lie within the part of the country

where thunder-rains form a far larger proportion of the total fall than in the west, and the records point clearly to temperature as the controlling factor.

THE VARIATIONS OF INTENSITY OF RAINFALL

The hourly record for Camden Square, London, which covers the 40 years 1881 to 1920, gives, in addition to values similar to those quoted, the duration of rainfall for each hour, showing not only how much rain fell but also the time during which it was falling. This enables us to compute the mean rate of rain per hour. The hours used in the case of this record are the even hours from 0 to 1, etc., instead of the centred hours from 0.30 to 1.30, etc., as in the previous case. It will be seen that, although the diurnal variation in the amount of rain in January is trifling, there is a distinct tendency for the duration to be greater at night, the maximum occurring between 2 and 3 a.m. In July the diurnal range of duration is reversed, the maximum occurring during the hours of daylight and the minimum almost precisely at the same hour as the winter maximum. The range of amount is well marked, varying from ·002 inch per hour at midnight to ·006 inch from 3 to 4 p.m. With regard to the mean rate of fall per hour, the winter values show comparatively small range, the tendency being for a double maximum, rising to a slightly marked peak at 3 to 4 a.m. and 2 to 3 p.m., but this may be accidental. In July the range is, however, conspicuously shown, the minimum, ·058 inch per hour, which is higher than the winter maximum, occurring between 6 and 7 a.m., and the maximum rising to ·133 inch per hour from 3 to 4 p.m.

London is, of course, situated nearly centrally in the district liable to summer thunderstorms, and the pronounced increase in the mean rate of fall per hour in the afternoon in the summer is evidently the best index of this fact.

MEAN DURATION AND AMOUNT OF RAINFALL AND MEAN RATE OF FALL PER HOUR. LONDON, 1881–1920

Hour.	January.			July.		
	Mean duration.	Mean amount.	Mean rate per hour.	Mean duration.	Mean amount.	Mean rate per hour.
a.m.	minutes.	in.	in.	minutes.	in.	in.
0—1 . .	3·5	·002	·042	2·1	·002	·069
1—2 . .	3·5	·002	·037	2·0	·003	·078
2—3 . .	3·9	·003	·050	2·1	·003	·089
3—4 . .	3·5	·003	·051	2·2	·004	·097
4—5 . .	3·3	·002	·042	2·8	·003	·062
5—6 . .	3·4	·002	·036	2·5	·002	·059
6—7 . .	3·3	·002	·039	2·5	·002	·058
7—8 . .	3·6	·002	·040	2·1	·002	·069
8—9 . .	3·5	·003	·042	2·1	·003	·070
9—10 . .	2·8	·002	·042	2·1	·002	·061
10—11 . .	3·1	·002	·038	2·3	·003	·091
11—12 . .	2·9	·002	·044	2·5	·004	·083
p.m.						
12—1 . .	2·7	·002	·044	2·6	·005	·111
1—2 . .	2·6	·002	·039	2·3	·004	·103
2—3 . .	3·2	·003	·049	2·2	·004	·103
3—4 . .	3·2	·003	·047	2·8	·006	·133
4—5 . .	3·1	·002	·043	3·0	·004	·086
5—6 . .	2·9	·002	·039	2·8	·004	·089
6—7 . .	2·9	·002	·048	2·7	·005	·099
7—8 . .	3·5	·003	·042	2·3	·004	·103
8—9 . .	3·5	·003	·046	2·5	·003	·080
9—10 . .	3·5	·002	·036	2·3	·003	·069
10—11 . .	3·3	·002	·041	2·3	·003	·080
11—12 . .	3·4	·003	·046	2·1	·002	·068
Total for day .	78·1	·056	·043	57·2	·080	·084
Day from 6 a.m. to 6 p.m. .	36·9	·027	·044	29·3	·043	·088
Night from 6 p.m. to 6 a.m.	41·2	·029	·042	27·9	·037	·080

Rather more information is available as to the mean rate of rainfall per hour during each month of the year than for each hour of the day, since a number of records of the duration of rainfall exist which have been less minutely analysed. Taking five representative stations in England and Wales for the ten years 1910 to 1919 from *British Rainfall*, the table on p. 111 is obtained.

This appears to justify the conclusion that over the whole year the mean duration of rainfall is roughly proportional to the amount of the fall, the mean rate of fall per hour showing little variation, and being, if anything, higher at the driest station, Worksop, than at the rainiest, Cray, where the total fall is fully three times as great. Some allowance must, no doubt, be made for the personal and instrumental individualities of the records (see p. 90, *ante*), but this could not possibly modify the values sufficiently to affect the general truth of the conclusion, more especially as four out of the five records in question were made with the same kind of gauge and all are chosen for their known high level of accuracy. There are, unfortunately, no data available for any station in an exceptionally rainy region, such as the Lake District, and it is possible that in such places a somewhat higher mean rate of fall may obtain; but apart from this possibility it would appear to be clear that regional variations of rainfall may, on the whole, be regarded as due to greater or less duration, rather than greater or less intensity, of fall.

Whilst the regional variation of the rate of fall is thus seen to be small, the seasonal variation is of considerably greater magnitude. At all the stations for which the data are given there is a well-marked

summer maximum, and this is most conspicuous at the stations of least rainfall. It seems abundantly clear that the higher rate of fall in summer in due to thunderstorm rains, and that rains of this type bulk more largely in the total summer rainfall at dry than at wet stations—a conclusion fully accordant with that previously arrived at from independent sources of information.

The statistics quoted in the above tables refer to average conditions, and are of interest to the climatologist as indicating the prevalence of, or tendency to, rainfall of varying intensity at different places and seasons. The range of intensity in individual showers is, however, extraordinarily great, and the outstanding instances of extremely high intensity which occur at intervals are worthy of study both from a climatological and economic point of view. They are of scientific interest on account of the light they throw on the natural laws controlling them, and of practical utility to the engineer as affording information necessary for sewage design and flood prevention.

The most accurate records of heavy falls of rain in short periods are naturally those obtained from self-recording gauges, but the more remarkable rains of this kind are so local that if it were necessary to depend entirely upon stations equipped with autographic apparatus it is probable that very few instances would be recorded. Observers of rainfall are therefore asked to make specially timed readings of their gauges during heavy storms and to add notes of the time and amount observed to their regular daily observations. In order that the records should be completely dependable it is important to notice that care should be taken to see whether the gauge

AMOUNT, DURATION, AND MEAN INTENSITY OF RAINFALL AT FIVE REPRESENTATIVE STATIONS IN ENGLAND AND WALES DURING THE DECADE 1910–1919

—	Camden Square, London. Casella Standard gauge.			Worksop, Notts. Halliwell gauge.			Southport, Lancs. Halliwell gauge.			Thirsk, Yorks, N.R. Halliwell gauge.			Cray, Brecon. Halliwell gauge.		
	Amount.	Duration.	Rate per hour.	Amount.	Duration.	Rate per hour.	Amount.	Duration.	Rate per hour.	Amount.	Duration.	Rate per hour.	Amount.	Duration.	Rate per hour.
	in.	hours.	in.	in.	hours.	in.	in.	hours.	in.	in.	hours.	in.	in.	hours.	in.
Jan. .	2·29	58·2	·039	2·02	49·8	·041	2·74	73·2	·037	2·57	76·9	·034	6·99	169·8	·041
Feb. .	2·09	50·5	·041	1·65	40·9	·040	2·25	58·5	·038	1·84	53·1	·035	7·36	151·4	·049
March	2·43	62·3	·039	2·00	49·3	·041	2·67	69·9	·038	2·12	66·0	·032	6·70	146·0	·046
April .	1·94	37·4	·050	1·18	24·8	·048	1·77	45·8	·039	1·45	36·8	·039	4·13	98·5	·042
May .	1·86	27·4	·068	1·83	29·0	·063	2·10	50·4	·042	1·70	39·3	·043	3·61	84·0	·043
June .	2·08	24·7	·084	1·75	24·3	·072	2·22	39·6	·056	2·18	39·3	·056	4·21	82·2	·051
July .	2·51	35·7	·070	2·33	30·0	·078	2·55	41·2	·062	2·71	44·9	·060	4·81	88·4	·054
Aug. .	2·57	32·5	·079	2·64	37·8	·070	3·57	61·1	·058	3·14	55·5	·057	7·00	108·4	·065
Sept. .	1·94	27·8	·070	1·49	27·0	·055	2·92	48·1	·061	1·82	34·1	·053	3·62	78·2	·046
Oct. .	2·20	41·7	·053	2·10	36·6	·057	3·46	58·3	·059	2·64	60·8	·043	6·77	128·5	·053
Nov. .	2·67	57·4	·047	2·17	42·7	·051	3·01	65·4	·046	2·63	65·9	·040	7·04	147·6	·048
Dec. .	3·25	69·4	·047	3·02	59·2	·051	3·93	90·3	·044	3·09	75·3	·041	10·87	211·6	·052
Year .	27·83	525·0	·053	24·18	451·4	·053	33·19	701·8	·047	27·89	647·9	·043	73·11	1494·6	·049

NOTE.—*The period covered by the observations from which this table is compiled, is not sufficiently long for the mean values to be regarded as true normals.*

is empty when heavy rain is anticipated, or if not, how much it contains; otherwise when taking a reading on the cessation of the fall some uncertainty will exist as to whether the whole of the amount measured fell during the time noted.

Numerous records obtained in this way are published annually in *British Rainfall*, and more than fifty years' observations are now available. Various attempts have been made to classify the data and to formulate a working definition of what constitutes a noteworthy intensity. This, of course, involves the use of a sliding scale, and the latter was arrived at by plotting all the readings received on squared paper and drawing a freehand curve dividing the falls too numerous to be worth putting on record individually from those sufficiently noteworthy to print. A second curve separated the noteworthy falls from those which might be designated "remarkable"; and, finally, a third curve put in a class by

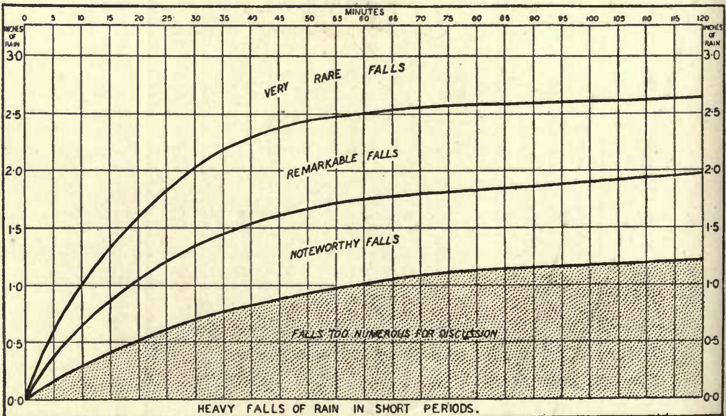


FIG. 51.—CLASSIFICATION OF INTENSE RAINFALLS—I. AMOUNT.

themselves a few outstanding records of such unusual intensity as to be called "very rare." The curves upon which the most recently adopted classification is based are shown in the accompanying diagrams up

LIMITS OF EXCEPTIONAL RAINFALLS

Minutes.	Noteworthy.		Remarkable.		Very rare.	
	Amount.	Rate per hour.	Amount.	Rate per hour.	Amount.	Rate per hour.
	in.	in.	in.	in.	in.	in.
10	·30	1·80	·65	3·90	1·00	6·00
20	·53	1·59	1·06	3·18	1·58	4·74
30	·70	1·40	1·35	2·70	2·00	4·00
40	·82	1·23	1·54	2·31	2·26	3·39
50	·92	1·10	1·67	2·00	2·42	2·90
60	1·00	1·00	1·75	1·75	2·50	2·50
70	1·07	·92	1·81	1·55	2·54	2·18
80	1·12	·84	1·85	1·39	2·57	1·93
90	1·15	·77	1·89	1·26	2·60	1·73
100	1·18	·71	1·92	1·15	2·62	1·57
110	1·21	·66	1·93	1·05	2·64	1·44
120	1·23	·61	1·94	·97	2·65	1·33

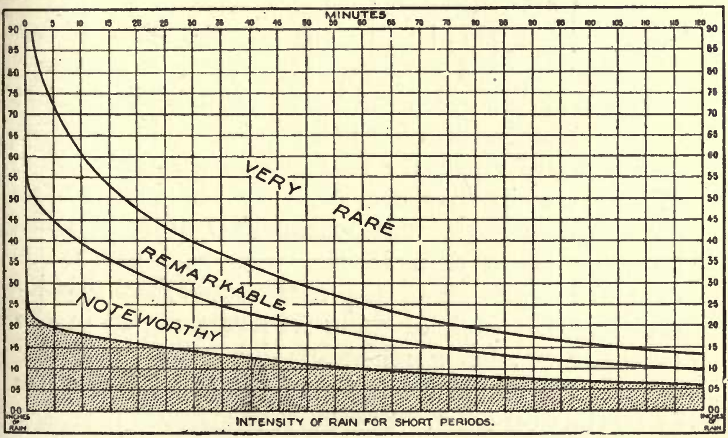


FIG. 52.—CLASSIFICATION OF INTENSE RAINFALLS.—2. RATE PER HOUR.

to two hours, and the table gives the limiting values for each class, together with the corresponding rates per hour. Beyond two hours the amount of data available is too meagre to enable the curves to be extended with confidence, and although it is clear that they are asymptotic to a straight line, it is equally clear that the straight line becomes meaningless if indefinitely prolonged.

Excluding from consideration all showers the intensity of which is not sufficiently great to bring them within the scope of the above table, and confining attention to rainfalls of two hours or less, the total number of instances recorded in the fifty-two years 1868 to 1919, inclusive, was 1,703. These were distributed as follows:

	England and Wales.					Scotland.	Ireland.	British Isles.
	S.E.	S.W.	N.E.	N.W.	Total.			
Total, 52 years .	825	378	126	104	1,532	111	60	1,703
Average per year .	16	7	4	2	29	2	1	32

Whilst the far greater number of instances recorded in the south-east of England than elsewhere is undoubtedly largely the result of the greater number of observers in that district, there is good reason for thinking that intense rainfalls are really more frequent there than in the west and north. A closer examination of the data emphasizes this by showing that even of those records grouped in the south-west and north-west the great majority occurred in the plains and very few in hilly districts or on the west coast. Similarly, the records obtained for Scotland and Ireland are nearly all from the east and centre.

An interesting instance of the contrast between the west of Scotland and the south-east of England was provided by a recent examination of the hourly records at Paisley, Glasgow, Fort William, and Ben Nevis Observatory.[1] At Glasgow during 39 years, at Paisley during 30 years, and at Fort William during 14 years, no instance was recorded of as much as ·70 inch in an hour. At Ben Nevis Observatory, one of the rainiest spots in the British Isles, the hourly records from 1884 to 1903, inclusive, show only three instances of as much as 1·00 inch in one hour, the highest recorded intensity being 1·30 inch during a winter snowstorm. In London, on the other hand, at least 11 instances of ·70 inch or more in an hour and 5 of 1·00 inch or more have occurred. On June 23rd, 1878, during a thunderstorm, 3·28 inches fell in 55 minutes, and 1·00 inch in 10 minutes, the intensity during the storm exceeding 5·00 inches per hour for nearly 30 minutes.

With regard to seasonal frequency, by far the greatest proportion of the cases occur in the summer, 76 per cent. of the whole being in the three months June, July, and August, and 33 per cent. in July alone. In Scotland, if the rather small number of records justifies the statement, there is a slightly greater frequency in August than in July. Mr. R. C. Mossman points out[2] that the curve of frequency in the south-east of England shows a close resemblance to that of thunderstorm frequency as observed in London, the latter being computed over

[1] The hourly records for Fort William and Ben Nevis are published in the *Trans. R. Soc. Edin.*, vols. xxxiv, xlii, xliii, and xliv.

[2] *British Rainfall*, 1913, p. 49.

a period of 167 years.[1] The values given are expressed as percentages of those for the whole year.

—	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
Noteworthy rains in S.E. of England .	0·1	0·3	0·0	1·0	9·2	23·2	32·9	20·3	8·6	3·4	0·6	0·4	100·0
Thunderstorms in London .	0·8	0·4	1·4	6·6	13·3	19·0	25·1	18·8	8·8	3·0	1·6	1·2	100·0

The only months in which a conspicuous variation between the two curves occurs are April and May. The comparative rarity of extremely intense rainfall in spring thunderstorms has often been commented upon. It is probably this fact which renders damage by lightning relatively more frequent in the late spring than in the thunderstorms of July and August.

Of the few noteworthy intense rainfalls occurring in the winter months it is interesting to notice that the proportion observed in the west of the country is very much larger than is the case in the summer. The majority are probably associated with the typical winter thunderstorms of the west coast, and occur with secondary cyclonic rainstorms, whereas the bulk of the summer intense rainfalls in the midlands and east are of convectional origin.

Turning to the "very rare" rainfalls, constituting the most intense of the three classes, existing tabulated data unfortunately refer only to falls of one hour or less, the numbers being therefore not strictly comparable with those quoted above:

[1] R. C. Mossman, "The Non-Instrumental Meteorology of London," *Q.J.R. Met. Soc.*, vol. xxiii, p. 289.

	England and Wales.					Scotland.	Ireland.	British Isles.
	S.E.	S.W.	N.E.	N.W.	Total.			
Total 52 years	22	10	4	4	40	3	0	43

This indicates that the regional distribution is closely analogous to that of "noteworthy" rains. A selection of the most remarkable rains of this nature recorded for the British Isles is given below:

Date.	Place.	County.	Amount.	Time.	Rate per hour.
			in.	h. m.	in.
May 8, 1912 .	Alexandria	Dumbarton	·26	0 1½	10·40
March 24, 1888 .	Chepstow	Monmouth	·33	0 2	9·90
June 14, 1917 .	Norwich	Norfolk	·47	0 2½	11·28
August 10, 1893.	Preston	Lancashire	1·25 ?	0 5 ?	15·00?
August 2, 1906 .	Guildford	Surrey	·89	0 8	6·68
May 30, 1902 .	Cambridge	Cambridge	1·10	0 10	6·67
August 14, 1914.	St. Peter Port	Guernsey	1·50	0 15	6·00
August 7, 1875 .	Canterbury	Kent	2·12	0 20	6·36
June 23, 1878 .	Camden Sq.	London	2·30	0 28	4·93
July 22, 1880 .	Cowbridge	Glamorgan	2·90	0 30	5·80
July 27, 1904 .	Cooling	Kent	2·66	0 45	3·55
June 26, 1895 .	Marlborough	Wiltshire	2·71	0 50	3·25
July 29, 1901 .	Wadhurst	Sussex	3·25 ?	0 55	3·55?
July 12, 1901 .	Maidenhead	Berkshire	3·63	1 0 ?	3·63?
May 30, 1903 .	Beddington	Surrey	3·50	1 0	3·50
May 26, 1911 .	Fareham	Hampshire	3·00	1 0	3·00

Practically all the instances on record of falls of 2·50 inches or more in an hour or less have occurred in districts with an annual average rainfall of less than 30 inches.

CHAPTER IX

THE FREQUENCY OF DAILY RAINFALL

In order to obtain more or less homogeneous data for the study of the frequency of daily rainfall, it is necessary to regard the rainfall day of twenty-four hours from 9 a.m. to 9 a.m. as a unit. Until the last few years the whole of the rainfall records made in the British Isles were measured in English inches, and with few exceptions the unit of measurement was one-hundredth (·01) of an inch. It followed, almost as a matter of course, that ·01 inch came to be regarded as a critical amount determining whether the day should be entered in the register as a day of rain or as rainless. The simplicity and convenience of this way of counting the number of so-called "rain-days" led to its widespread adoption among rainfall observers, and although Symons early recognized that it was not without drawbacks, he acceded to the suggestion to print the number of days with ·01 inch of rain or more for every station in the annual tables in *British Rainfall*. The rule once accepted has never been changed, and has long been given official sanction in the definition "A rain-day is a day on which ·01 inch of rain or more is recorded." In order to give more precision to the definition, it is necessary to quote the words of the instruction drafted by the British Rainfall Organization for the guidance of observers:

"*Small Amounts.*—If the gauge contains less than one-hundredth

(·01) of an inch, but more than half that amount, it should be entered as ·01, while if there is less than half that amount, the few drops may be thrown away and the day entered as if no rain had fallen."[1]

The amount of water representing ·01 inch in an ordinary rain gauge is so small that with a flat-bottomed measure, even if very accurately graduated, an otherwise insignificant bias to high or low reading, or a trifling displacement of the meniscus due to opacity of the glass (see p. 41, *ante*), gives rise to a considerable want of uniformity in the records from different stations. With a slight error in the lowest graduation mark on the measure, which would be quite immaterial at any other point, a still greater discordance is introduced. With the more extensive use of the "Camden" pattern glass[2] no doubt the want of harmony with regard to the number of "rain-days" observed would disappear, but the re-equipment of the whole body of 5,000 observers must be extremely gradual.

The use of the metric system for official rainfall recording in this country since 1914 has introduced a fresh element of discordance. The recognized "rain-day" for observers measuring rainfall in millimetres is a day on which 0·2 mm. or more is recorded, the critical half-unit, corresponding to ·005 inch, being, of course, 0·1 mm. In a 5-inch rain gauge ·01 inch represents 3·2 c.c. of water, whilst 0·2 mm. represents 2·5 c.c., and thus an actual discrepancy in the unit of measurement is added to the already existing sources of uncertainty.

In considering statistics of rainfall frequency or incidence based upon the "rain-day" as above

[1] British Rainfall Organization, *Rules for Rainfall Observers*, Rule 11.

[2] See p. 40, *ante*.

defined, it is necessary always to bear in mind the "errors" introduced by the causes described; the more so as in many cases the utmost care on the part of the observer will not entirely eliminate them. The range of the regional distribution of rainfall frequency is not large, being proportionately much less than that of the amount of rainfall, and in any attempt to construct maps of the number of "rain-days," the fact that the differences observed between adjacent stations are sometimes greater than those between districts representing the extremes of climate is sufficient proof that the method is radically wrong.

The natural remedy for the original difficulty, that arising from the very small unit employed, is to increase the unit to a larger quantity, thus ensuring that days of insignificant drizzle, or of fog or dew deposit, shall be effectively excluded from the count, and at the same time raising the minimum quantity considered to an amount at which the instrumental and personal error can be safely ignored. It is true that this method leaves out of the counted days some on which unmistakable showers will have occurred, but the main consideration involved in rainfall measurement is the deposition of precipitation in sufficient quantities to be of real significance.

The smallest value on the respective scales at which the inch and millimetre measurements virtually coincide is 1·0 millimetre or ·04 inch; 1·0 millimetre of rain in a 5-inch rain gauge gives 12·7 c.c. of water; ·04 inch gives 12·9 c.c. The amount is sufficiently large to outweigh the small errors occasioned by the difficulty of accurate measurement and sufficiently small to include all days of significant rainfall. Frequency values of days with 1·0 mm. or ·04 inch of rain have been published for some years in the

Monthly Weather Report of the Meteorological Office, and a consideration of the subject based upon the records for 1919 is given in *British Rainfall* 1919, from which part of the above is reprinted.

It is at the moment premature to speak definitely, but there appears good reason to believe that the hitherto almost insuperable difficulty of studying the regional distribution of rainfall frequency will largely disappear if the data are determined by the adoption of the proposed new definition: "A *wet day* is a day ending at 9 h. (G.M.T.) on which 1·0 mm., or ·04 inch, or more, of rain is recorded."

Until a much larger amount of data have been examined with the above definition as a basis for determining daily frequencies, it is possible only to deal with records based on the old and inadequate definition of a "rain-day." The method adopted in *British Rainfall* for minimizing the difficulties referred to is admittedly imperfect from a scientific point of view, though it is the only practicable one. It consists in selecting from the available data representative records for which the observed numbers of "rain-days" appear to be in reasonable harmony with the majority in their respective districts, and assuming these to be accurate. The number of records dealt with in recent volumes has been one hundred, and it has been possible to choose these in such a way as to be nearly equably distributed over the whole of the British Isles.

The only average values available in cartographic form indicating the approximate regional distribution of "rain-days" are from stations selected in this way. They refer to the twenty years 1892–

1911, and they must be accepted only subject to the reservations implied above. The distribution of frequency resembles that of amount of rainfall, the wetter districts of the west having rain on more days than the drier districts of the east, but there are plain indications that the frequency varies from east to west or, to be more precise, from east-south-east to west-north-west, rather than with altitude, though the effect of the land contour is quite apparent, and there is no doubt that if the map had been based upon a larger number of records, the effect of configuration would have been more marked. The uplands of Wales, the Pennines, and the whole of the west of Scotland are included within the area with an average of more than 200 days, and the whole of Ireland, except a narrow strip of the east coast, has more than that number. The occurrence of the 200-day line on the Yorkshire Wolds and over Aberdeenshire, where the easterly-wind rains are most common, is a noteworthy feature. The falling-off towards the south-east of England is also conspicuous, the Thames Valley, the lowlands of East Anglia and part of the south coast being marked by less than 175 rain-days, and the Thames Estuary being the only part of the country where the average number of rain-days may be believed to fall below 150. The western half of Ireland and that portion of the west of Scotland which is not partially sheltered from rain-bearing winds by the north of Ireland have uniformly more than 225 days with rain. In the still more westerly and exposed coastal strips of both countries 250 days occur. Thus it may be said that on the average of the year, in the extreme west of the British Isles it rains on five days out of seven, and in the extreme south-east on only three.

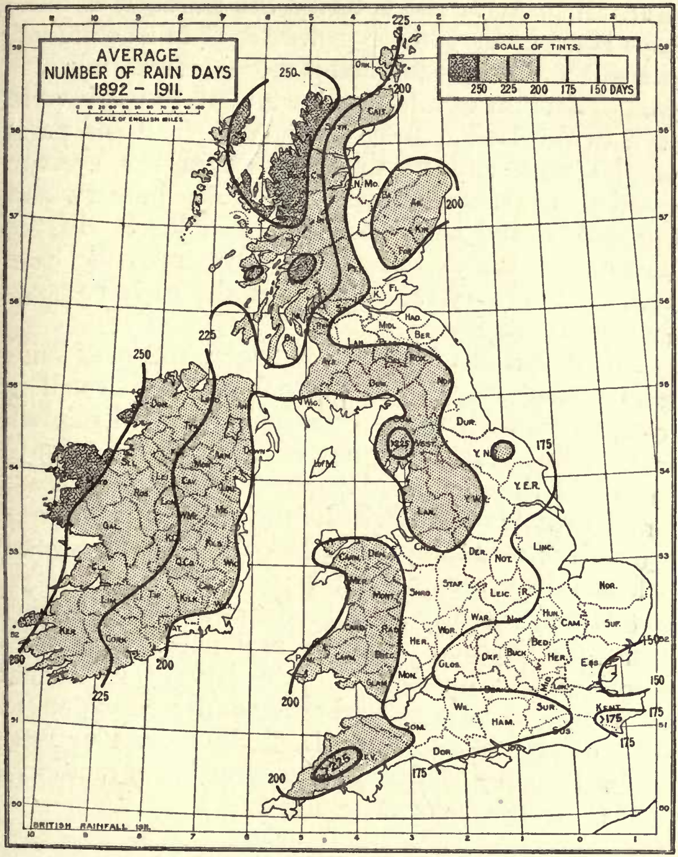


FIG. 53.—REGIONAL DISTRIBUTION OF AVERAGE FREQUENCY OF RAIN-DAYS, 1892–1911.

The general values for the greater divisions of the country are:

	days.		days
England . . .	184	Scotland . . .	216
Wales . . .	209	Ireland . . .	223
England and Wales .	187	British Isles . . .	204

In all parts of the country the number of rain-days is normally greater in winter than in summer, the seasonal frequency being more or less similar to that of amount of rain in the west and nearly inverse to it in the east. In the west of Ireland and parts of the west and north of Scotland the average number of rain-days rises to 25 in January and December, and barely falls to 15 in June. In the Thames Estuary the mid-winter months have approximately 15 rain-days, and the early summer months about 10.

The deviations from the average number of rain-days which occur in individual years are small in comparison with the fluctuations of actual rainfall. In only one year, 1903, out of the 17 years 1903 to 1919 did the general departure from the average for the whole of the British Isles reach 10 per cent., equivalent to 20 days, and in only 6 of these years did the departure exceed 5 per cent., or 10 days. There is apparently little tendency also to deviation from the normal type of regional distribution. Maps of the number of rain-days in individual years show a nearly general excess or defect, expressed by a displacement of the isopleths to east or west rather than any tendency to an inversion or modification of the normal arrangement.

DROUGHTS AND RAIN-SPELLS

The incidence of rain-days, apart from their frequency over the year taken as a whole, is most conveniently studied by an examination of the occurrence of protracted spells of consecutive rain-days or of consecutive rainless days. For this purpose the definitions adopted in *British Rainfall* and commonly accepted in this country are :

"A *rain-spell* is a period of fifteen or more days every one of which is a rain-day.

"An *absolute drought* is a period of fifteen or more days no one of which is a rain-day.

"A *partial drought* is a period of twenty-nine or more days the mean rainfall of which does not exceed ·01 inch per day."

The unduly small unit of ·01 inch certainly detracts from the value of these definitions. It frequently happens that a deposit of dew or condensed fog yields as much as ·01 inch in the rain gauge, and this is quite rightly entered in the record as if it had been true rain. Since dew and fog are most frequent and copious during the type of weather when absolute drought is prevalent, many records of drought are marred by this technicality. There is certainly a strong case for ignoring very small amounts in recording an "absolute drought," and it is probable that a definition based on the "wet day" or day of ·04 inch (1·0 mm.) would have many advantages. Similarly, it is clearly absurd to classify as a "rain-spell" a run of consecutive days with small deposits of dew, such as may be the concomitant of anticyclonic weather, and if any day with less than ·04 inch were held to break a "rain-spell," there would be no possibility of this happening.

The occurrence of droughts of both classes defined is very largely confined to the east, or drier, half of the British Isles, and they are rare, though not unknown, in the rainy districts of the west. In London (Camden Square) during the 62 years 1858 to 1919 there were in all 69 absolute droughts, or rather more than one per year on the average. The greatest number in one year was four in 1858 and 1868, and 15 out of the 62 years in the period had none. The longest absolute drought recorded at the

station was 29 days from March 18 to April 15, 1893.

On the average of 32 years the area of the British Isles experiencing absolute droughts is roughly 50 per cent., the area in individual years varying from about 96 per cent. in 1887 to about 10 per cent. in 1902. The greatest duration recorded at any one of the representative stations selected for study was 44 days from March 4 to April 16, 1893, at Whittlebury, Northants.; but at a number of stations in the south-east of England no measurable rain was recorded for more than 60 days during that memorably dry spring.

Partial droughts, or periods of more than four weeks with a mean rainfall of not more than ·01 inch per day, are slightly less common than absolute droughts. They occur on the average in any one year over only about 40 per cent. or two-fifths of the British Isles, the largest area involved in any year being about 82 per cent. in 1887, and the smallest about 4 per cent. in 1902.

The great spring drought of 1893 already mentioned was so outstanding for duration that the map showing its regional distribution is reproduced. The only districts in which it did not occur were the west of Scotland and Ireland, whilst over the whole of the south of England and Wales the length exceeded 50 days. South-east of a line from Cornwall to the Wash the period was more than 75 days, and more than 100 days were affected in the south-eastern counties, rising to more than 120 days in a few places. The most extreme record quoted in *British Rainfall* was at North Ockendon, near Romford, where during the 128 days from March 2 to July 7 only 1·23 inch of rain fell.

FIG. 54.—DISTRIBUTION OF THE GREAT SPRING DROUGHT OF 1893.

Over the country as a whole, rain-spells are more frequent than absolute droughts, though individually they seldom affect so large an area. On the average of the 17 years 1903 to 1919 the area of the British

Isles experiencing rain-spells was approximately 71 per cent. In the very rainy year 1903 the percentage rose to about 89, and in 1913 it fell to about 56. In every year considerable areas in the west of Scotland and Ireland never fail to record three or four periods of this nature, and in 1903 as many as 3 occurred over half the area of the British Isles, and as many as 5 over nearly a quarter. Whilst the mean duration of rain-spells is only slightly longer than that of absolute droughts, they are, in some instances, liable to extend to considerably longer periods, and in 9 out of the 17 years available for discussion at least one rain-spell has extended over 50 days or more. The most protracted period of this nature yet put on record occurred in 1914 in the west of Ireland. On this occasion rain fell daily from January 23 to April 13, inclusive, 81 days, at Killarney in co. Kerry, and at Newmarket-on-Fergus in co. Clare, the total rainfall at the former station being no less than 26·19 inches, or a mean daily fall of ·32 inch.

In striking contrast to the great frequency and occasional very long duration of rain-spells in the west, they are extremely rare in the east, where well-marked rainy periods are seldom sufficiently long to satisfy the definition. Thus in the 62 years 1858 to 1919 only 7 rain-spells have occurred in London. In 55 years during this period no rain-spell has been observed, and in no single year has more than one occurred. The greatest duration of any rain-spell in London in the whole period was 20 days, from December 23, 1877, to January 11, 1878.

Rain-spells are of greatest frequency in mid-

winter, being associated with persistent periods of orographical rain. Whilst they are probably least frequent in the late spring, fairly frequent instances occur of rain-spells of the winter type in the early spring months.

CHAPTER X

TYPES OF REGIONAL DISTRIBUTION—I

In Chapter II an attempt has been made to adopt a broad classification of three types of rainfall grouped in accordance with the origin of the ascending air-currents which give rise to the precipitation. Study of any map of daily rainfall, especially in conjunction with a map showing the distribution of barometric pressure at the time, readily enables these types to be identified when their characteristics are sufficiently marked; but it must again be urged that, owing to the gradual transition from one class of rainfall to another, complete identification with one type may not necessarily be possible. Some improvement in this respect might be found if the detail of observation allowed of the separation of individual showers.[1] Short of a greatly increased use of self-recording rain gauges, this is virtually impossible.

In mapping the regional distribution of the amount of precipitation, a limiting factor is therefore introduced by the circumstance that all but a few of the observations available refer only to the period of twenty-four hours from 9 a.m. to 9 a.m. It sometimes happens that the outlines of an indi-

[1] The word "shower" is used not in its popular sense of a sprinkle of rain, but as signifying an individual and identifiable continuous rain, as distinct from any other.

vidual shower which has taken place during the day are obscured by the occurrence of other rainfall, maybe the tail-end of a previous shower or the beginning of a subsequent one. Again, the identity of a rainstorm may be lost by its stretching over portions of two days; since, owing to the movements of the rain-areas from place to place, the fact of a rigid hour of observation usually means that the measurement is made at a different phase of the storm at each station. It is clearly impracticable to obtain a sufficiently large number of observations specifically timed to establish the identity of a mobile rain-shower, and in practice it has been found necessary to adhere to the rainfall day as the unit of time and to map the fall of a single day or group of days. In spite of the drawbacks mentioned, this method has thrown some valuable light on the types of regional distribution occurring with rain-storms of recognizable origin.

Attempts have been made to cope with the problem by obtaining evidence of the hour of commencement or termination of an outstanding shower. Two pairs of interesting examples may be mentioned as illustrative of the conditions associated with "showers" of completely different types. The opportunity to construct maps of this kind is so rare that it must not necessarily be assumed that on the few occasions when it has been possible the conditions were sufficiently representative to be regarded as typical, but they are nevertheless suggestive.

The first relates to the remarkable snowstorm of Christmas and Boxing Day, 1906. The area over which no snow fell on these two days is shown in the map in solid black. It will be observed that the

storm swept over a tract of country from 150 to 250 miles wide, stretching from north-west to south-east. This tract was parallel to the path of a secondary barometric depression which crossed the British Isles simultaneously. The storm may therefore be classed as cyclonic. Owing to the striking nature of the storm and the date of its occurrence, it was possible to obtain nearly 2,000 records giving some information as to the time when snow commenced to fall. These data when plotted on a map gave a basis for Fig. 55. In this map the isopleths refer to the hour of commencement, each zone representing an interval of two hours. It will be seen that the isochronous lines run from north to south and indicate that the front of the oncoming snowstorm moved from west to east, whilst the limits of the fall on the north-east and south-west, where the black area on the map begins, show that the front edged away to the southward as it progressed. The time of commencement was before noon on December 25 in the north-east of Ireland; two hours later snow was beginning to fall in Islay; and by 4 p.m. the south-western mainland of Scotland was affected. The speed of advance apparently varied little, being about twenty miles per hour throughout, though it was less in the north. At midnight of December 25-26 the front had progressed to a line stretching from Yorkshire to Sussex, and in East Anglia snow did not commence till after 2 a.m., the whole passage of the front from Londonderry to Yarmouth occupying some 17 hours. An attempt to map the hour of termination of this shower failed owing to the want of harmony of the records.

A second example of isochronous mapping of a

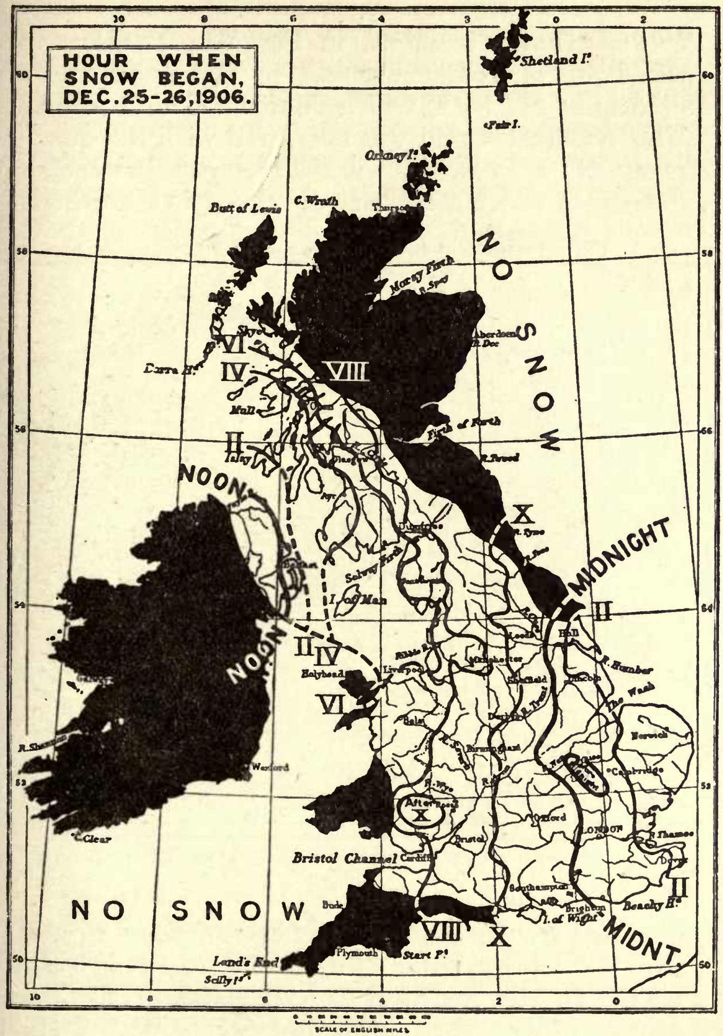
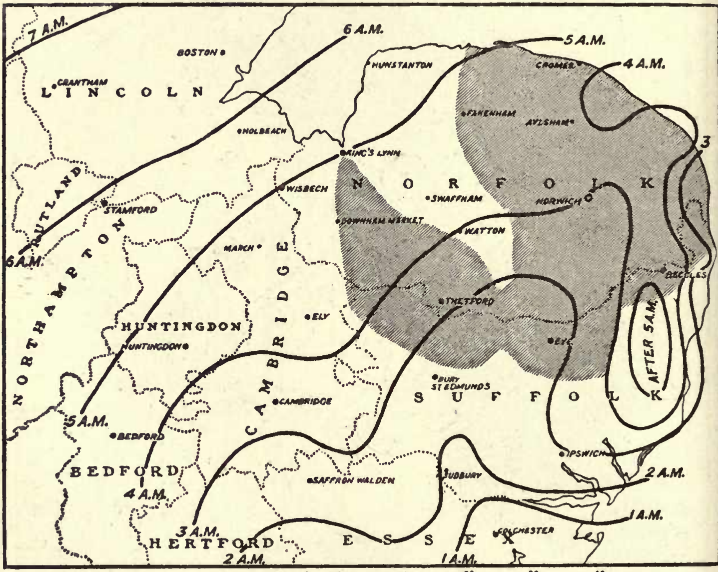


FIG. 55.—SNOWSTORM OF DECEMBER 25–26, 1906. ISOCHRONOUS LINES.

cyclonic shower is shown in Fig. 56. It refers to the hour of commencement of the great storm of August 26, 1912, which culminated in Norfolk.[1] This remarkable rain was associated with the movement of a small but well-developed barometric depression which travelled very slowly in a northerly

HOUR OF COMMENCEMENT OF RAIN AUGUST 26TH, 1912.



SCALE OF MILES 10 5 0 10 20 30 40

THE SHADING REPRESENTS THE AREA WITH MORE THAN FOUR INCHES ON AUGUST 25–26.

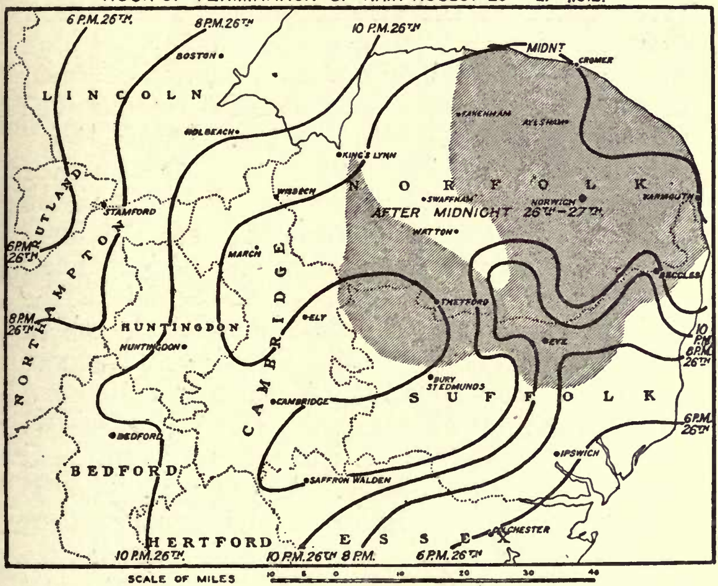
FIG. 56.

direction from a point off the east of Kent to near Cromer. Beyond the limits of the map rain began to fall in the south-east of England in the late evening of August 25. The line representing 1 a.m. on the 26th is seen in the neighbourhood of Col-

[1] For fuller details of this great rain, see *British Rainfall*, 1906, p. 19.

chester, and the time of commencement was later by about an hour for every 10 miles to the north-westward. The progressive movement was on a fairly straight front, not unlike that of the snowstorm of December 25-26, 1906, except in the neighbourhood of the east coast, where it was more irregular.

HOUR OF TERMINATION OF RAIN AUGUST 26TH-27TH, 1912.



THE SHADING REPRESENTS THE AREA WITH MORE THAN FOUR INCHES ON AUGUST 25-26.

FIG. 57.

Fig. 57, showing the hour of termination of rain in the same storm, presents some different features. In the south-east and north-west of the area mapped, where the variation in commencement was greatest, the hour of termination was identical, viz. 6 p.m. Rain continued longer in the centre of the area and longest of all, viz. till after midnight, in a large,

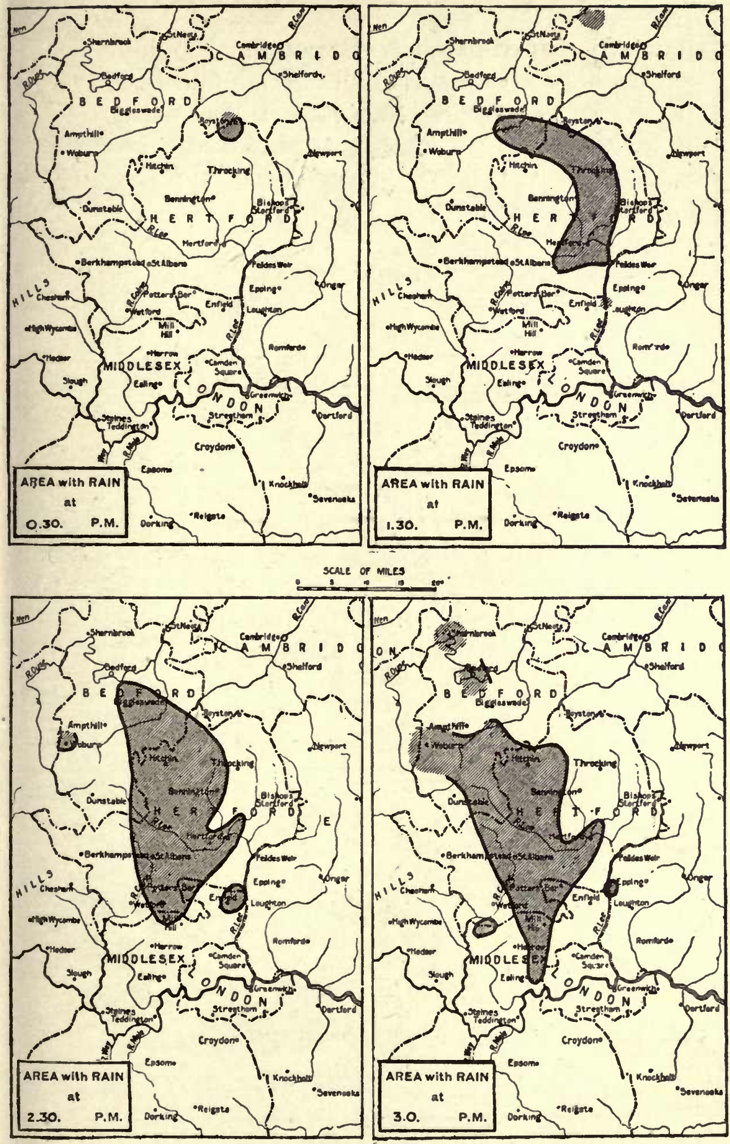
irregularly shaped patch, corresponding roughly with the region of greatest rainfall. It should be stated that, as was found to be the case with the snowstorm described above, the data relating to the hour of termination were less consistent than those of the hour of commencement.

The above examples refer, as has been stated, to precipitation of the cyclonic type. Two further examples which it is possible to cite are quoted from the work of Mr. J. Fairgrieve[1] on the time-relations of rainfall in storms of convectional origin. The first of these refers to the great "Derby Day" thunderstorm of May 31, 1911. The method followed by Mr. Fairgrieve was to plot on separate maps all available data determining the area over which rain was actually falling at specific times. The series shown in Figs. 58 to 61 shows the development of a small rain-area in the north of Hertfordshire, and its gradual spread westward and southward till it reached Woburn and London. During the later afternoon the rain-field extended slowly across the Thames and two new centres of activity appeared in Surrey. At 5.15 p.m. (Fig. 63) these three centres gradually approached one another, and at 5.30 p.m. (Fig. 64) had coalesced into one large rain-field, which at first expanded and finally by 8.30 p.m. broke up into detached areas and disappeared. The greatest intensity was observed at the point of junction of the three separate rain-fields on Banstead Downs between 5.15 and 5.30 p.m.

An interesting supplementary map (Fig. 68) shows the outline of the clouded area surrounding the rain-field at 3 p.m. It will be seen that the storm moving from the north was confined to a relatively

[1] See *British Rainfall*, 1911, p. 33.

THUNDERSTORMS OF MAY 31st, 1911.



FIGS. 58, 59, 60, 61.—RAIN-FIELDS, MAY 31, 1911.

FIGS. 62, 63, 64.—RAIN-FIELDS, MAY 31, 1911.

THUNDERSTORMS OF MAY 31st, 1911.

FIGS. 65, 66, 67.—RAIN-FIELDS, MAY 31, 1911.

narrow tract, especially where it crossed the River Thames, clear sky approaching within about a mile of the rain-area near Ealing. The separate storms which developed in Surrey were already heralded by a cloudy belt two hours before rain began to fall.

THUNDERSTORMS OF MAY 31st, 1911.

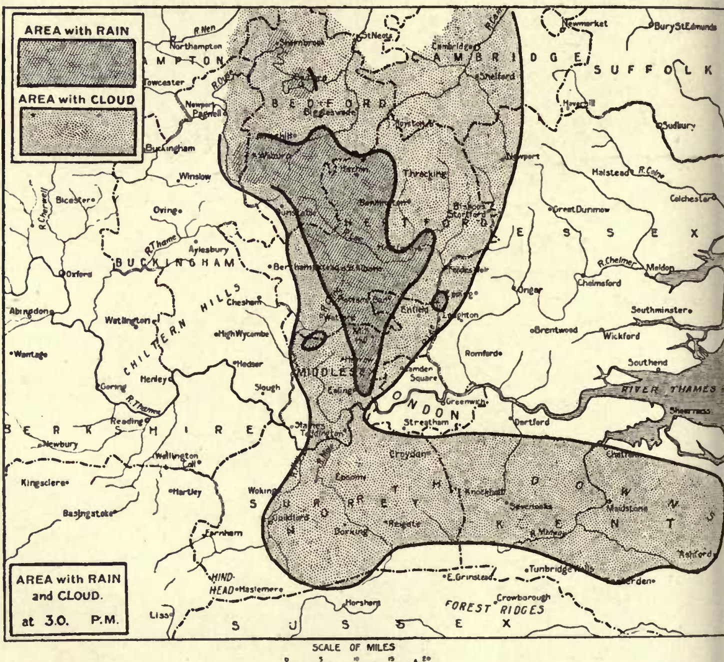


FIG. 68.—CLOUD AND RAIN-FIELDS, MAY 31, 1911.

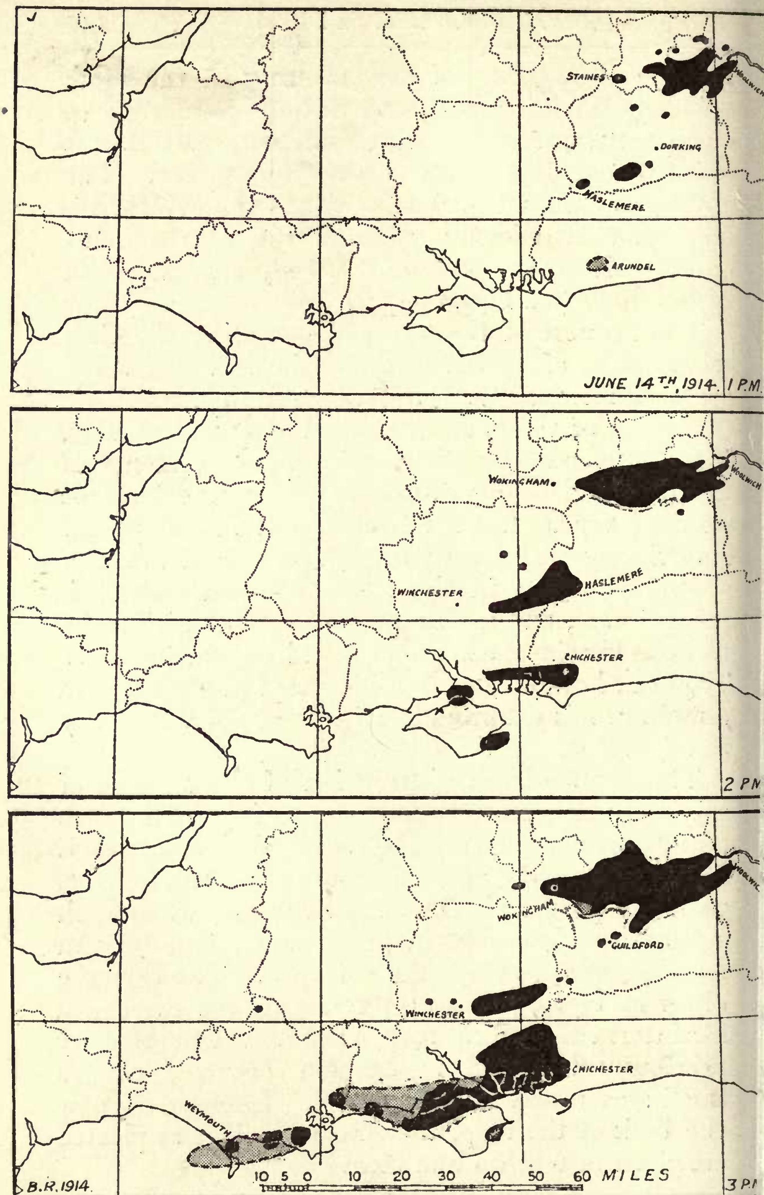
Another series of Mr. Fairgrieve's maps[1] refers to the thunderstorms of June 14, 1914, which covered a somewhat wider area. The storms developed in numerous small detached patches stretching from

[1] See *British Rainfall*, 1914, p. 48.

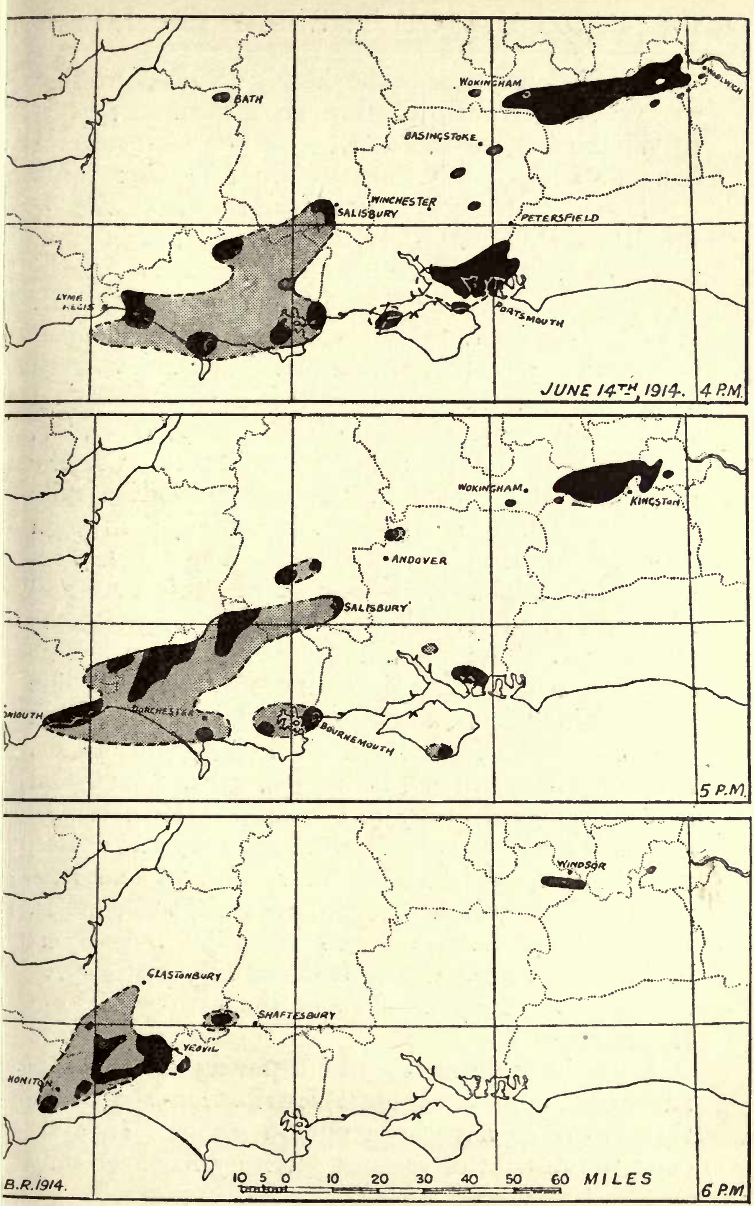
London to the east of Devonshire. In the more westerly district lack of data made it impossible to outline the rain-fields with certainty, and it was necessary to introduce some assumptions. The portions of the rain-fields for which the evidence is incomplete are shown in a lighter tint, and the boundaries, where not definitely fixed, are drawn in broken lines (see Figs. 69–74).

The interest of these maps illustrating the time relationships of rainfall lies largely in the well-marked contrast between the slow, steady march of the single rain-front of the cyclonic rainfall and the irregular, hesitating, and comparatively rapid movements of the rain-field during storms of the convectional or thunder type. In the former case the development is obviously connected with the passage of the low-pressure centre; in the latter no such control is recognizable, and fresh centres of activity giving rise to isolated rain-patches appear at irregular intervals There is, however, some evidence of propagation in a more or less definite direction, and some tendency to alignment.

The detail of the distribution of the amount of rainfall during local thunderstorms is sometimes so minute that a very close network of observations is necessary in order to define the run of the isohyets with any precision. The few occasions when such storms have occurred in urban areas, especially in London, afford interesting evidence. The example given in Fig. 75 (p. 145) refers to the extremely local storm of June 16, 1917, when rain of an intensity previously unknown in London occurred over a small area round Campden Hill. In order to show the basis of the map, the actual readings as plotted are given in tenths of an inch.



FIGS. 69, 70, 71.—RAIN-FIELDS, JUNE 14, 1914.



FIGS. 72, 73, 74.—RAIN-FIELDS, JUNE 14, 1914.

It is of interest to note the sharply defined zero line passing from Stratford, through Liverpool Street, to Wimbledon, to the south-west of which no rain fell. Parallel to this line and from 1½ to 2 miles north-west of it, the line of ·50 inch runs from Woodford through Dalston and Chelsea to Teddington, and then turns northward to Sudbury and eastward to Wood Green, nearly encircling the storm area. Within the district thus enclosed a well-defined area with more than 1 inch of rain stretched from Tottenham on the north-east to Twickenham on the south-west and extended to Ealing, Wembley, and Highgate on its north-west margin. On the south-east the 1-inch line ran about half a mile north-west of the ·50-inch line, passing through Canonbury, King's Cross, and Walham Green. More than 2 inches fell between Finsbury Park and Richmond, and extended to Willesden Green on the north-west. The rainfall gradient on the south-east was still further intensified, the 2-inch line approaching within a quarter of a mile of the 1-inch line in the neighbourhood of Kensington and St. Pancras. More than 3 inches appears to have fallen in two separate areas, one lying to the north of Regent's Park, the other, of a somewhat larger size, stretching from Paddington to Barnes and thoroughly well outlined by half a dozen good records. Within this area more than 4 inches fell over about half a square mile, the highest reading, 4·65 inches, being obtained by a gauge in the garden of Cam House.

A considerable number of instances of thunder-rains exhibiting a regional distribution similar to that described have been put on record. In some cases the district of greatest intensity has been only

FIG. 75.—THUNDERSTORM TYPE

one of a number of centres of activity, in others it has been apparently a completely isolated phenomenon. An example of the former kind was the storm of June 3, 1908. On this day, whilst the

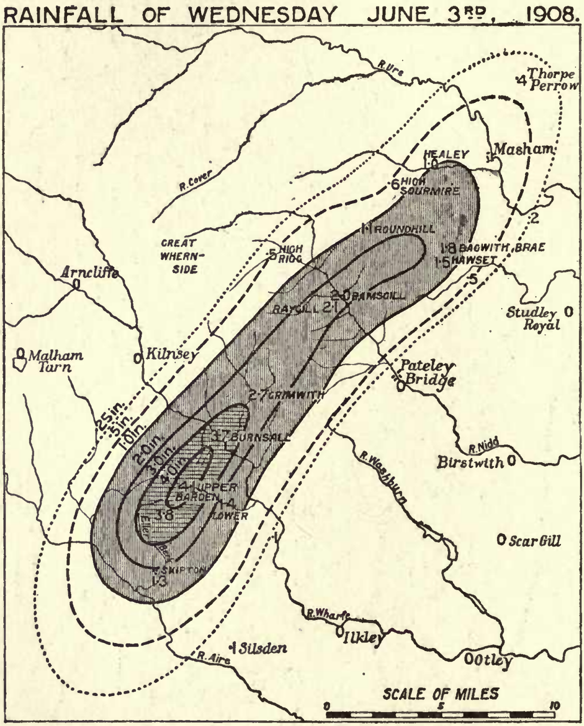


FIG. 76.—THUNDERSTORM TYPE.

greater part of England and Wales was without rain, and practically none fell in Scotland or Ireland, thunderstorms took place over three tracts of country respectively, in Kent, from Hertfordshire to Hampshire, and from Bristol to the north of York-

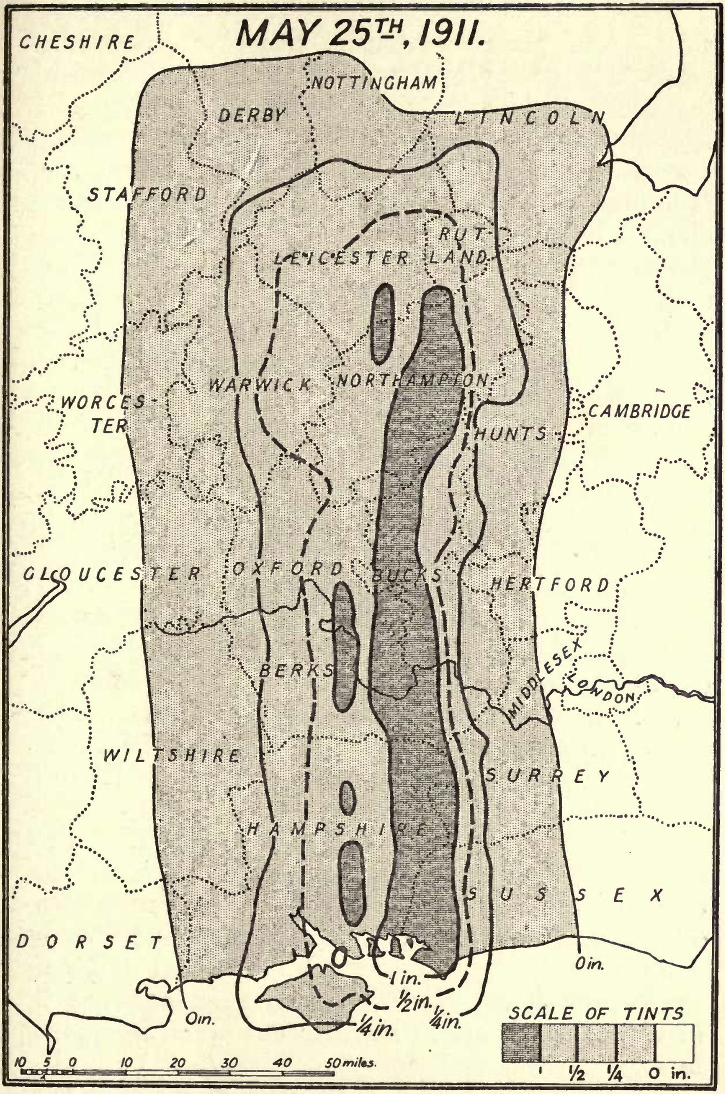


FIG. 77.—MODIFIED THUNDERSTORM TYPE.

shire. The greatest intensity was observed over a small and nearly isolated elliptical area between Skipton and Masham, with its culminating centre on Embsay Moor. The map shows that there was an extremely steep rainfall gradient at this point, the falling-off in the amount measured amounting to about 4 inches in 5 miles. It will be observed that the amount of data available for constructing the map was considerably less than in the case of the London storm of June 1917, but sufficient observations were available to define the run of the isohyets with fair precision.

The third example of this type of distribution, shown in Fig. 77, refers to a storm of less pronounced intensity than the two already described. In this case, however, the interest of the map is enhanced by the fact that the rain-area, which was fairly extensive, was completely isolated, no rain occurring in any other part of England. It should be remarked that the clean-cut and sharply defined outline of the rectangular block of country marked out on the map is not due to paucity of data. The district in question is better provided with stations than any other of equal size in the world, and several thousand readings were plotted in the construction of the map. It will be seen that the gradient or rate of increase of the fall from zero to the belt of maximum on the west is less abrupt than on the east, and that the belt of maximum fall itself is duplicated. The occurrence of parallel strips of heavy rainfall in association with thunderstorms is highly characteristic. Further examples are given in Figs. 78, 79, and 80.

The rainfall of June 5, 1910, gives an instance of a widespread thunderstorm affecting a definite tract

of country. The double tract of maximum fall shown by the bifurcation of the 1-inch area and the alignment of the patches with 1·50 inch and 2 inches is well shown. It is probable, judging by the general outline of the rain-area, that the rainfall of the day may have been partially cyclonic or transi-

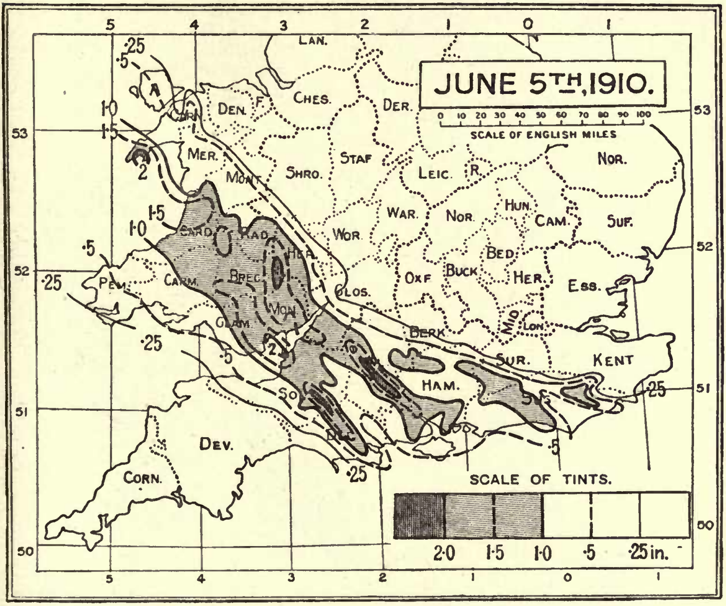


FIG. 78.—CONVECTIONAL-CYCLONIC TYPE.

tional between the convectional and cyclonic types.

The occurrence of parallel strips of heavy rainfall separated by more or less rainless areas is illustrated by the map for July 17, 1918, shown in Fig. 79. On this day more than an inch of rain fell in a number of well defined parallel bands stretching from south-

west to north-east. The best marked of these extended from Winchester to Sutton-on-Sea, a distance of about 175 miles, the width nowhere

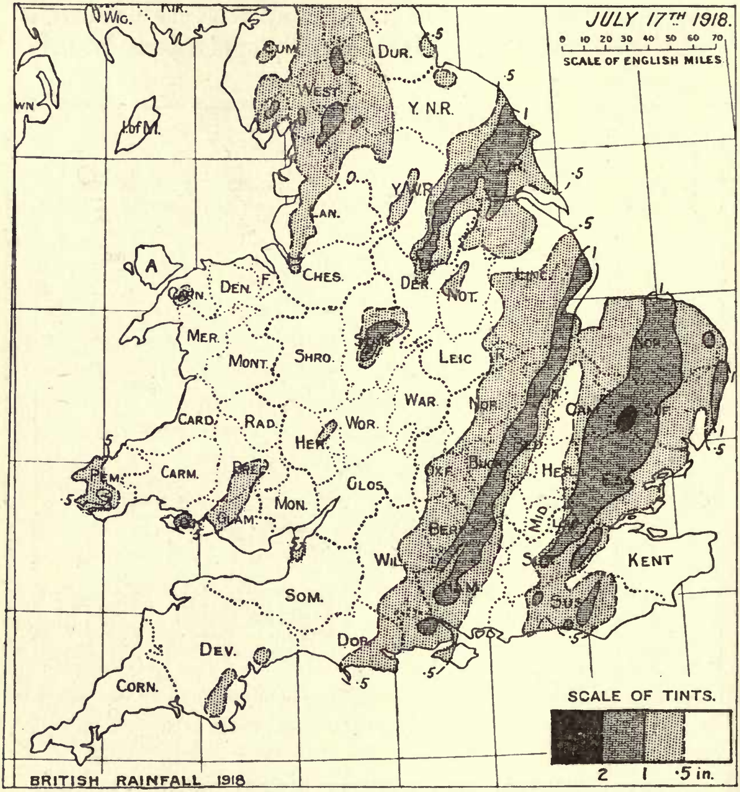


FIG. 79.—PARALLEL TRACTS OF THUNDERSTORM RAIN.

exceeding about 12 miles. A somewhat wider band stretched from Cromer to Dorking; it was within this belt that the rainfall was most intense, the principal centres being from Bury St. Edmunds

southward, and in the east of London. A third, but in this case interrupted, belt of heavy rain occurred still further to the east, between Lowestoft and Brighton, and similar discontinuous strips lay to the north-west with patches of heavy rain at intervals from Plymouth to Scarborough, from Swansea to Wearhead, and from Haverfordwest to Windermere. It is difficult to assert positively the alignment of the rudimentary strips in the west, though the tendency of the splashes to be grouped in lines parallel to the quite unmistakable eastern strips is conspicuous.

It must not be supposed that thunderstorm-rains invariably fall into the arrangement suggested by the preceding examples. On occasions it will be found that the grouping of the rain-splashes is suggestive of propagation from a number of centres from which tongues of heavy rain appear to branch out and extend for various distances. In other cases no definable pattern is even remotely suggested and the distribution of the rain appears to be promiscuous. It is, of course, possible that the failure to identify any specific arrangement in these cases may be due to the inherent shortcomings of the method, to which reference has already been made.

No completely satisfactory explanation has been given of the tendency for thunder-rains to occur in straight lines. It is clear that the suggestion of propagation along the line must be abandoned, since observations of the time of occurrence of rain do not, as a rule, bear this out. An exception, however, must be made in the case of the hailstorm of July 16, 1918, two days previous to the occurrence of the rainfall depicted in Fig. 79, above. The hailstorm in question, which was investigated in

great detail by Mr. J. E. Clark,[1] occurred in an extremely narrow strip of the south-eastern counties from the Isle of Wight to Lowestoft, and was severe only over a ribbon-like tract from half a mile to a mile wide, stretching from near Leith Hill to North Bromley, a distance of 22 miles. The evidence goes to show that the time at which the storm commenced varied from 1.15 a.m. at Calshot to 4.20 a.m. at Felixstowe, 135 miles distant. Intermediate observations give the speed of progression as between 36 and 73 miles per hour. In a nearly simultaneous parallel line of storm extending from Craven Arms in Shropshire to Huddersfield, the speed of transmission appears to have been from 50 to 60 miles per hour. Mr. Clark lays special emphasis on the relatively small wind-velocity both in the lower and upper atmospheric strata, showing clearly that the movement cannot be regarded as merely due to the storm-centre being blown bodily across the country. The phenomena observed in this instance do not appear to be those of line-squall, and suggest rather the interaction of two masses of air at different temperatures, inclined at an angle so that their contact would be not unlike that of the blades of a pair of scissors when being closed.

The repetition at intervals of parallel bands of heavy rainfall may possibly be explained on the hypothesis of wave-movements on a large scale in the upper air. Such wave-movements are also probably associated with the formation of the parallel strips of cloud not infrequently seen. The strongly marked alternation of dry and wet areas within the band is well brought out by Fig. 81,

[1] See *Q.J.R. Met. Soc.*, vol. xlvi, p. 271.

FIG. 80.—ALIGNMENT OF RAIN-SPLASHES IN THUNDERSTORM.

showing the rainfall over a straight line from Carmarthenshire to the mouth of the River Thames during a typical thunderstorm on July 22, 1907.

Rain of an undoubted cyclonic origin not infrequently simulates convectional rainfall in the

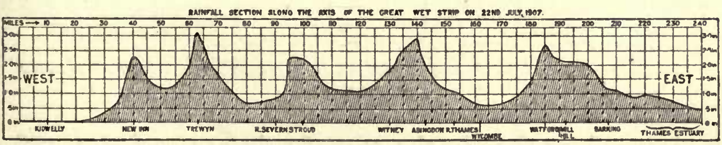


FIG. 81.—ALTERNATING DRY AND WET AREAS IN THUNDERSTORM.

arrangement of the wet areas. This seems to occur, however, more with irregularly moving secondary

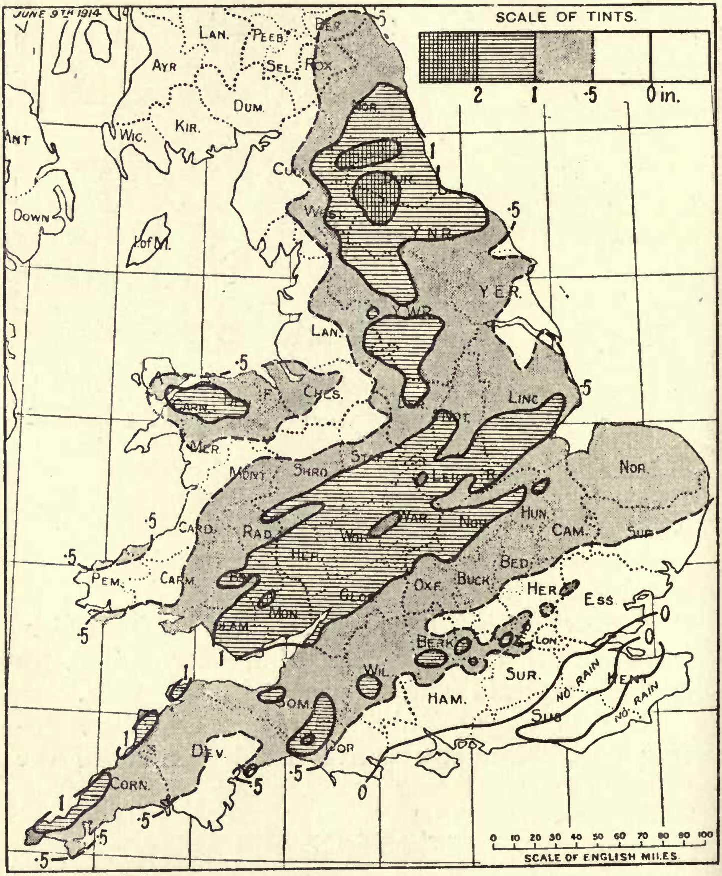


FIG. 82.—SECONDARY CYCLONIC RAIN SIMULATING THUNDERSTORM DISTRIBUTION.

depressions than in the case of primary cyclones, and it is probable that an instance like that of June 9,

1914 (Fig. 82), although mainly cyclonic, must be classed as intermediate between the two types.

The types of distribution associated with the

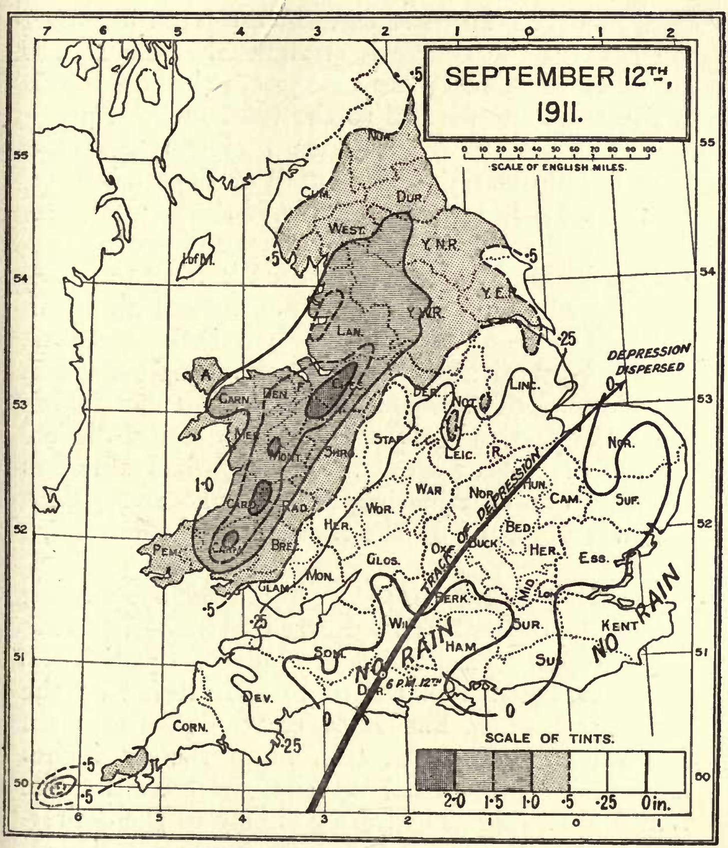


FIG. 83.—DISTRIBUTION WITH PRIMARY CYCLONE.

passage of primary cyclonic systems are of considerable diversity. It is clear that the areas over which rain falls, more particularly the regions of heaviest

fall, are largely controlled by the position of the centre of the depression. It is not always easy to fix the latter with great precision, and some of the anomalies observed may be attributed to uncertainty on this score. In most cases investigated in which the path of the centre is straight, the rain-area is found to be more or less elongated, the major axis being, as a rule, parallel to the track of the depression, but this is by no means always the case. Fig. 83, illustrating the rainfall of September 12, 1911, is a fairly typical example of the normal relation. In this instance the depression moved north-eastward from Dorsetshire to the Wash, and rain fell over the whole of England except around the south and east coasts. As much as ·50 inch, however, occurred practically nowhere east of a line about 80 miles distant on the left of the track, 1 inch falling ten miles farther away. About 100 miles distant we find a belt of areas with more than 2 inches forming the culminating axis. Only very slight rain was observed on the right, or east side, of the track.

On December 9, 1914 (Fig. 84), when a somewhat similar depression-track occurred farther east, passing through the Straits of Dover, there is no direct evidence with regard to the rainfall on the right-hand side, but it is clear that the main axis was again on the left, more than 2 inches falling about 80 miles to the north-west. The 1-inch area approached more closely to the depression-centre than in the case previously mentioned. The straight, sharply defined zero-line, marking the limit of the rain-area on the north-west, 130 miles from the track, and the nearly equally straight isohyet of ·50 inch 20 miles nearer are of special

interest, and no doubt can exist that their trend is controlled by the direction of movement of the depression.

Dr. Mill[1] has laid special emphasis on the great frequency with which the main part of the rain

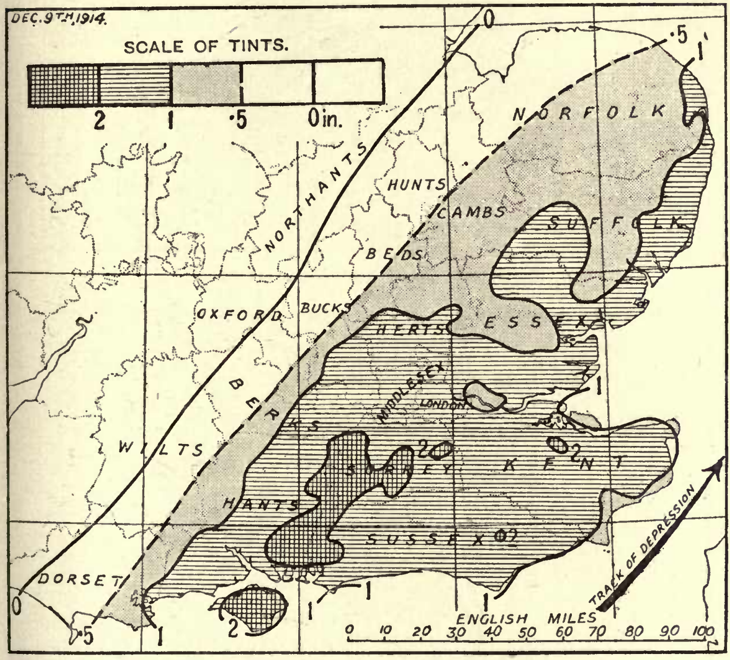


FIG. 84.—DISTRIBUTION WITH PRIMARY CYCLONE.

associated with the passage of cyclonic systems occurs on the left-hand side of the track, and this seems to hold good even when, as in Fig. 85, the main axis of the rain-splash lies in an abnormal direction. Apart from this unusual feature the rainfall of April 6,

[1] See *British Association Reports*, 1904, "On the Unsymmetrical Distribution of Rainfall about the Path of a Barometric Depression."

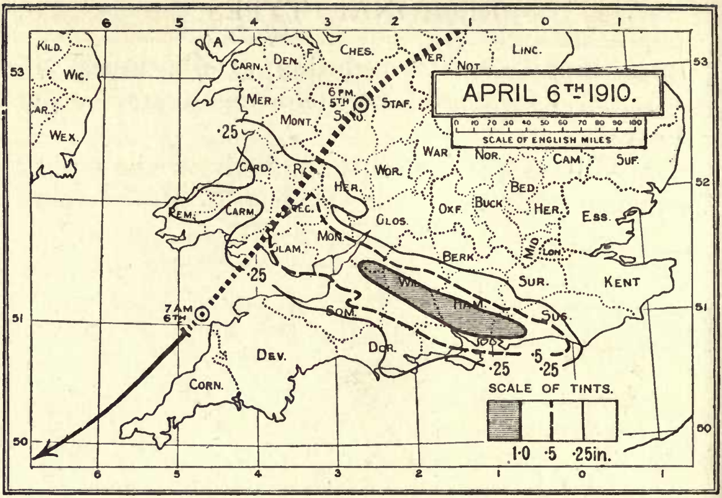


FIG. 85.—ABNORMAL CYCLONE TRACK.

FIG. 86.—ABNORMAL CYCLONIC DISTRIBUTION.

1910, is peculiarly interesting as illustrating an instance of a depression following a track from north-east to south-west.

An apparent exception to the above generalization is shown in Fig. 86. The track in this instance appears to have passed through a lane of relatively slight rainfall, between two parallel tracts of heavy

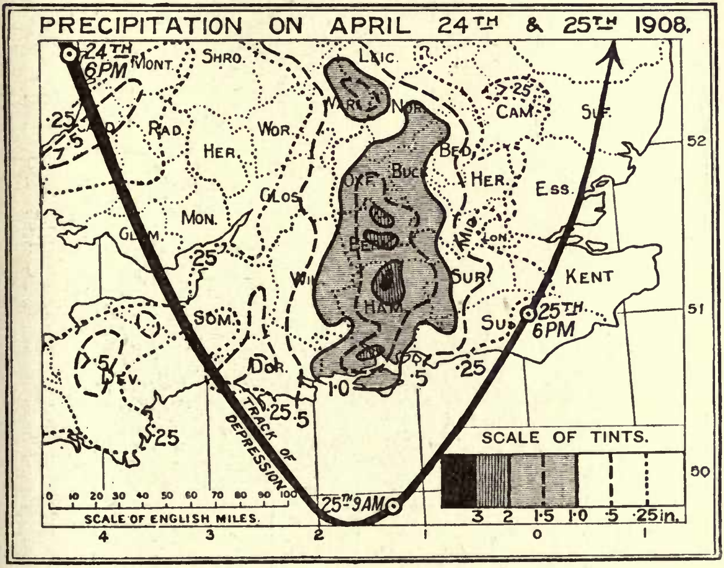


FIG. 87.—PRECIPITATION WITH CURVED CYCLONE TRACK.

fall lying respectively on the left and right hand, the heaviest rain occurring locally in the latter. Instances are occasionally met with in which the whole of the important part of the fall has occurred on the right.

The tendency for the rain to occur on the left is accentuated in the case of curving tracks. In the case of curvature to the left, the heaviest fall is

usually found within the loop, as will be seen in the case of the cyclonic snowstorm of April 24 and 25, 1908 (Fig. 87). On this occasion the area of heaviest fall is less elongated than is usual with a

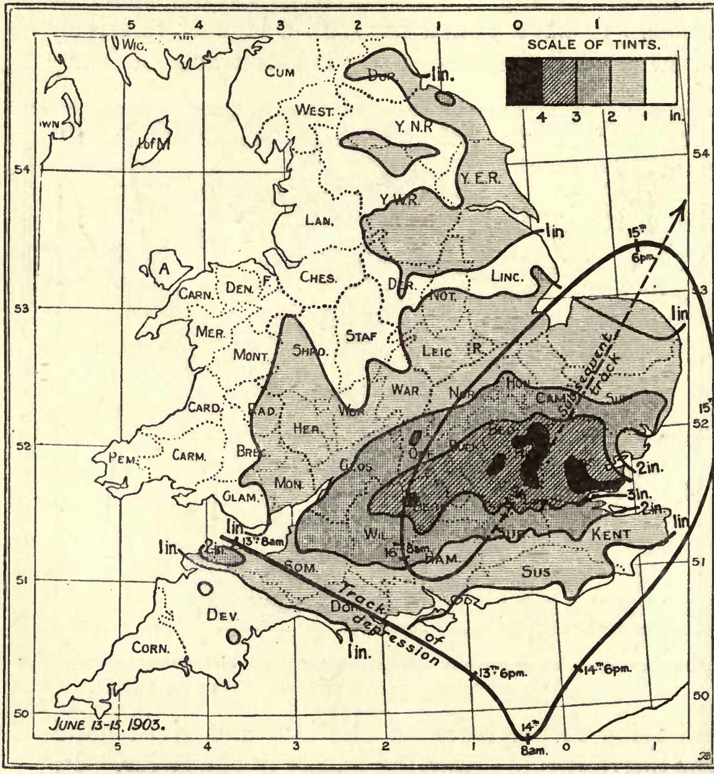


FIG. 88.—DISTRIBUTION WITH CYCLONE TRACK LOOPING TO LEFT.

straight track and approaches more nearly to it than in the examples quoted above, more than 1 inch[1]

[1] In the case of snowfall, the measurements given are invariably the equivalent of the snow as rain-water, i.e. the yield of the snow when melted.

falling less than 40 miles distant, and as much as 3 inches within 80 miles.

A closely analogous example occurred in the case of the remarkable cyclonic rains in the valleys of the Thames and Lea on June 13, 14, and 15, 1903. On the first of these three days a primary depression crossed the south-west of England from the Bristol Channel to the Isle of Wight, passed over the English Channel to a point near Havre by the following morning, and then turned north-eastward through the Straits of Dover. Off the coast of East Anglia on the morning of June 15 the track again turned to the left and curled round till it re-entered England by way of the Wash. From this point it moved south-westward into Hampshire, and again turned abruptly to the left early on the 16th, afterwards moving north-eastward into the North Sea. It thus formed a complete loop, encircling the south-east of England and doubly encircling a tract of country stretching from Hampshire to Norfolk. During the whole period of this extremely unusual journey rain was falling persistently though not very heavily over areas lying on the left of the track. The districts which lay within the loop were thus constantly dominated by the system for about three days without intermission. The duration of the "shower" at Camden Square, London, was 58½ hours, from 1 p.m. on June 13 to 11.30 p.m. on the 15th, yielding a total fall of 3·44 inches. It is probable that even greater durations occurred in Hertfordshire and Essex, where the total fall was in places as much as 5 inches.

An instance of a looped cyclone-track in which the deflexion was to the right hand, instead of to the left as on June 13–15, 1903, occurred on June 11–12, 1919. The map showing the fall of June 12

(Fig. 89) indicates that in this case the heaviest rain appears to have fallen on the *outside* of the loop, and to have culminated in three well-marked areas about equidistant from it. It is true that there is

FIG. 89.—DISTRIBUTION WITH CYCLONE TRACK LOOPING TO RIGHT.

little direct evidence of the fall within the loop, since this was almost entirely over the sea, but all the land area included had a relatively small fall. It will be observed that the generalization that the principal rainfall is on the left of the track still holds good.

CHAPTER XI

TYPES OF REGIONAL DISTRIBUTION—II

A FEW outstanding examples of cyclonic rainfalls of a very exceptional nature which have occurred during the past few years may be allowed to fall into a special group. They may be roughly divided into two classes according to the barometric conditions. In the first class the depression, usually comparatively small, has apparently been nearly stationary or subject to slight uncertain movements during a period varying from a few hours to several days. In the second class the track of a travelling depression has shown an abrupt turn to the right, the centre of heavy rainfall, in each case extremely pronounced, lying on the left of the track and near the point of deflexion.

In the case of nearly stationary depressions, the principal feature of the rainfall is its persistence and the localization of the greatest falls near the low-pressure centre. An instance of this occurred on October 26–28, 1909, when more than 3 inches of rain fell over a strip of the south-east coast, culminating in falls of more than 6 inches in Kent. During the three days ill-defined and shallow low-pressure centres moved in an irregular manner over an area comprising the English Channel, the north of France, and the southern extremity of the North Sea, and more or less continuous rain fell over the

adjacent districts. On the 26th from 2·50 inches to 3·50 inches was measured in East Sussex; on the 27th the south-east of England was still wet, but rain was most pronounced in Brittany; whilst on the 28th, when the depression was moving away rather more rapidly northward, there was a tremendous downpour in the east of Kent, falling with a north or north-west wind and a rapidly rising barometer. On this day no rain was recorded to the north-west of a nearly straight line drawn from Barnstaple to Hull, and less than ·50 inch beyond an equally straight line from Weymouth to Hunstanton, these lines being parallel to the then track of the depression. More than 1 inch fell widely in Hampshire, Surrey, and Kent, increasing rapidly to more than 3 inches over about 100 square miles between Folkestone and Sandwich. This probably represented the main axis of the rain-belt, and lay some 20 miles to the left of the track.

Each of these three days represented a phase of the storm, the full effect of which, so far as England is concerned, is represented in Fig. 90. The track of the depression-centre was so indefinite and its movements were so slight until the last day that it is not practicable to indicate it on the map.

On July 29 to August 3, 1917, a close repetition of the conditions just described occurred, affecting in all a somewhat wider area, but culminating, so far as its maximum rainfall was concerned, in nearly the same district. During this period the pressure conditions in the west of Europe were of a very unusual nature. As is often the case with heavy rainfall, the associated depressions were shallow and the slight variations of pressure made it difficult to follow the changes with precision. They were,

however, somewhat similar in character to those of October 26–28, 1909.

Heavy rain fell daily in the south-east of England,

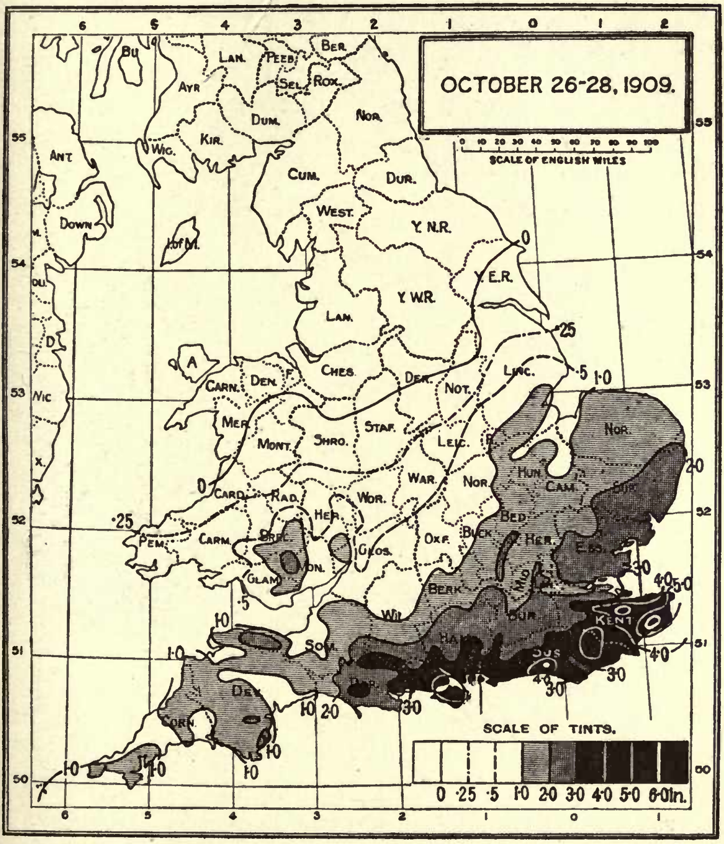


FIG. 90.—DISTRIBUTION WITH NEARLY STATIONARY DEPRESSION.

and the excessive fall culminated in a remarkable manner in Kent, where over a considerable area the total fall for the six days exceeded 8 inches, while

FIG. 91.—DISTRIBUTION WITH NEARLY STATIONARY DEPRESSION.

one station at Canterbury recorded as much as 10 inches.

During the individual days of this period the distribution of rainfall exhibited a tendency to the

linear arrangement characteristic of thunderstorm-rain, and it is probable that the minor secondary depressions were associated with a type transitional between convectional and purely cyclonic precipitation; but taking the whole spell of six days as representing a single rainfall episode, the conditions were undoubtedly primarily of the cyclonic type. The map, Fig. 91, shows that a zero line ran from south to north nearly coinciding with the west coast of England and Wales, and that heavy rain fell only in the east of the country, more than 3 inches being practically confined to the area south-east of a line from Hampshire to the Wash. In the centre of greatest fall at Canterbury rain was falling in all for 95·2 hours during the six days. The rate of fall was by no means great, seldom reaching ·20 inch per hour. The longest spell of unbroken rain was from 6.30 p.m. on July 30 to 0.20 a.m. on August 2, a period of 53·9 hours, and the longest spell without rain was from 3.50 a.m. to 4.35 p.m. on the 30th, 12·7 hours. At no other time did rain cease for as much as eight hours.

Turning to the second class of very excessive cyclonic rainfalls, those associated with a definite deflexion to the right of the track of the depression, it is as well to remark that such deflexion has possibly occurred without the accompaniment of remarkable rainfall. No collated evidence at present exists on this point. It is, however, certainly a matter for comment, as has been pointed out in *British Rainfall*, that no fewer than four instances—one in Ireland, one in Scotland, and two in England, in each case giving rainfall of an unprecedented nature—should have occurred under closely analogous pressure-conditions.

Fig. 92 refers to the great cyclonic rainstorm of August 24–26, 1905, in eastern Ireland. The whole shower covered rather more than 24 hours, so that the commencement and termination respectively overlap the 24th and 26th, but by far the bulk of the fall occurred on the rainfall day dated the 25th. In a paper communicated to the Royal Meteorological Society in January 1906,[1] Sir John Moore pointed out that the low-pressure system associated with the storm lay off the coast of Kerry and Cornwall on the morning of August 24. At 8 a.m. on the 25th it was situated near the Scilly Isles, whence it travelled slowly northward through St. George's Channel, its centre passing near Dublin early on the morning of the 26th. At this point it suddenly changed its course and turned eastward, passing across North Wales and England into the North Sea near the mouth of the Humber. Rainfall was general over Ireland, and widespread, though less conspicuous, in the west of England and Wales. The areas of heaviest fall were in the east of Ireland, more than 2 inches occurring to the east of a line joining co. Cork and co. Antrim, and more than 4 inches in parts of cos. Down, Meath, Dublin, and Wicklow, the three last-named having over 300 square miles with more than 5 inches of rain. The localization of these extremely wet areas near the point at which the abrupt change in direction of the cyclone track occurred and on its left-hand side is the principal feature of interest. The rain fell with wind from a north-easterly quarter, and there appears to be no doubt that it was the interference of this relatively cold drift in the path of the moisture-laden south-westerly winds on the south side of the advancing

[1] See *Q.J.R. Met. Soc.*, vol. xxxii, 1906, pp. 1–10.

AUGUST 24TH–26TH, 1905.

FIG. 92.—DISTRIBUTION WITH DEFLECTED CYCLONE TRACK—I.

depression which gave rise to the ascending currents necessary for the condensation of rain in such large quantities. The fact that the rain was nearly, if

not quite, as great in the lowlands of co. Meath as on the mountains of Wicklow, coupled with experience gained in the investigation of similar cyclonic storms in later years, seems to disprove the suggestion put forward by Sir John Moore that the heavy fall on the high land south of Dublin was induced by the configuration of the ground, and though it is possible that this may have been an aggravating factor, it was certainly not the prime cause.

The second instance observed of remarkable rainfall associated with a deflected cyclone track occurred on August 25 to 26, 1912, precisely seven years after the great Irish rainfall. The details of this storm, which has already been mentioned on pp. 134–135, *ante*, were fully described by Dr. H. R. Mill in his paper to the Royal Meteorological Society in January 1913,[1] and amplified in *British Rainfall*, 1912. The low-pressure system associated with the rain appears to have originated as a secondary situated near Brittany on the evening of August 25. At 7 a.m. on the 26th a small but well developed depression lay with its centre off the coast of Kent, and during that day it moved northward very slowly, reaching a point near Cromer by 6 p.m. On the following morning the centre had moved to the eastern side of the North Sea after making an abrupt change of direction to the east or right-hand side in the interval, thus showing great similarity to the conditions described in connection with the rainfall of August 1905. Rainfall was fairly widespread in the south of England and Wales on the 25th, yielding over 1 inch in places, particularly in a strip of the east coast from Dungeness to Yarmouth, where the great "shower," which

[1] See *Q.J.R. Met. Soc.*, vol. xxxix, 1913, pp. 1–28.

was continued throughout the following day, commenced in the early hours, and was therefore partly included in the measurement for the 25th. The fall measured on the morning of the 27th, including the remainder of the shower, affected about the same area as that of the previous day, but it was locally of far greater amount. More than 1 inch of rain was mainly confined to the East Midlands and East Anglia, and more than 3 inches almost entirely to Norfolk. In the east of that county over 1,000 square miles experienced a rainfall of more than 4 inches, and more than 7 inches fell at Sprowston, near Norwich. As far as East Anglia is concerned, the rainfall of the two days combined may certainly be regarded as closely representing the yield of the single shower, and the map (Fig. 93) deals with the total fall for the whole period. It will be observed that except for a rainy area in the upper Severn Valley, probably principally associated with other secondary depressions than that under discussion, as much as 2 inches was confined to a small patch in Kent and a well-defined area on the east coast stretching from Sutton-on-Sea to Clacton and extending inland to Kettering. Within this district and especially to the eastward the amount of the fall increased, gradually on the outskirts and more abruptly towards the culminating point near Norwich. More than 800 square miles in north-east Norfolk experienced a rainfall of 6 inches or more and about 250 square miles of 7 inches or more, the highest amounts registered being 8·25 inches at Sprowston, and 8·09 inches at Brundall. The whole of this fell in about 24 hours.

There is no evidence as to the rainfall over the North Sea, so that it cannot be asserted positively

that the whole of the fall associated with the depression, or even the major part of it, fell on the left of the track, but the slight diminution of the amount recorded between Norwich and the coast suggests

RAINFALL AUGUST 25TH-26TH, 1912

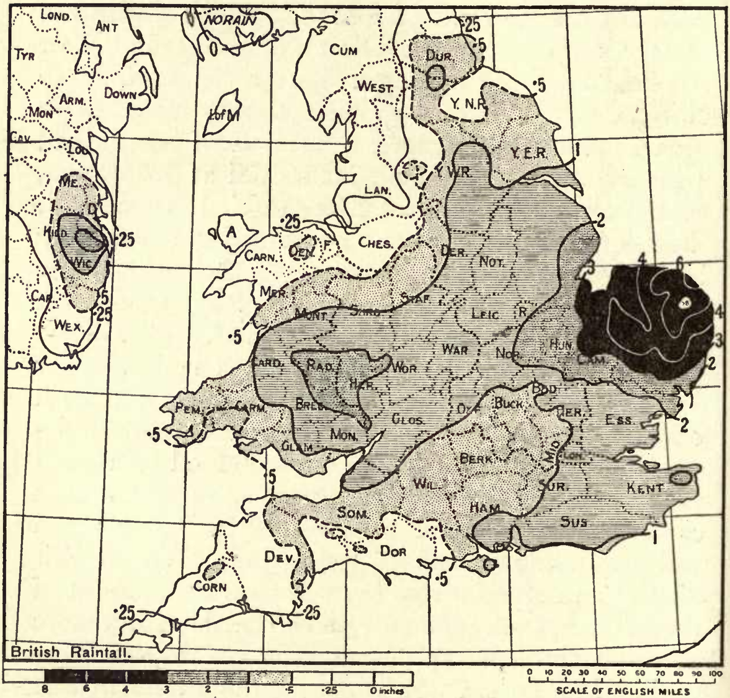


FIG. 93.—DISTRIBUTION WITH DEFLECTED CYCLONE TRACK—2.

that the main rain-field was centred on the land. The precise position of the point of deflexion of the track is not known, but it is fairly clear that it bore much the same relation to the heavy rainfall area as in the case of the Irish rainfall. The close

resemblance of the two storms is certainly very striking.

On September 25–26, 1915, a third repetition of the circumstances narrated above occurred in the

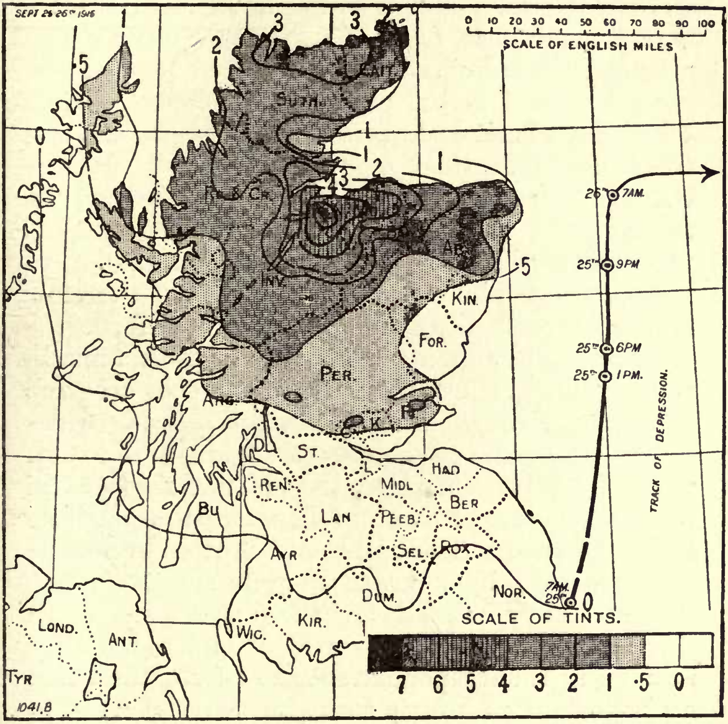


FIG. 94.—DISTRIBUTION WITH DEFLECTED CYCLONE TRACK—3.

east of Scotland. The depression on this occasion moved slowly northward during the 25th from near Newcastle-on-Tyne on a track between 50 and 100 miles from the western shores of the North Sea. Shortly after 7 a.m. on the 26th, when about 40

miles east of Peterhead, the track turned sharply to the east and the depression passed away to the Continent. The distribution of rainfall during the two days, nearly all of which occurred on the 25th, is shown in Fig. 94. More than ·50 inch was observed over the northern half of Scotland, and more than 2 inches over nearly 6,000 square miles. The principal fall culminated to the east of Inverness in the counties of Nairn and Elgin, where more than 5 inches was measured at a number of stations and the remarkable total of 7·91 inches at Dalcross Castle. The position of this area with reference to to the point of deflexion of the cyclone track is 120 miles to the left, and the correlation of the two phenomena is highly probable in view of the close parallelism with the cases previously described.

The fourth, and in some respects most remarkable, of the great cyclonic rains of this class occurred on June 28, 1917. Though considerably less widespread than some of the great individual rainstorms which have been mapped, the amount recorded in the central cores of highest fall, situated respectively on the Quantock Hills and round Bruton, in Somerset, surpassed by a broad margin any previously recorded daily rainfall for the British Isles. In this case the whole of the area of high rainfall lay in a fairly thickly populated part of England, and no important part of it took place over the sea, so that it was possible to outline the rain-areas with exceptional precision.

The barometric conditions associated with this rainfall are broadly indicated by the cyclone track marked on the map (Fig. 95). The course of the depression, which was of small size, was approximately from west to east, along the English Channel,

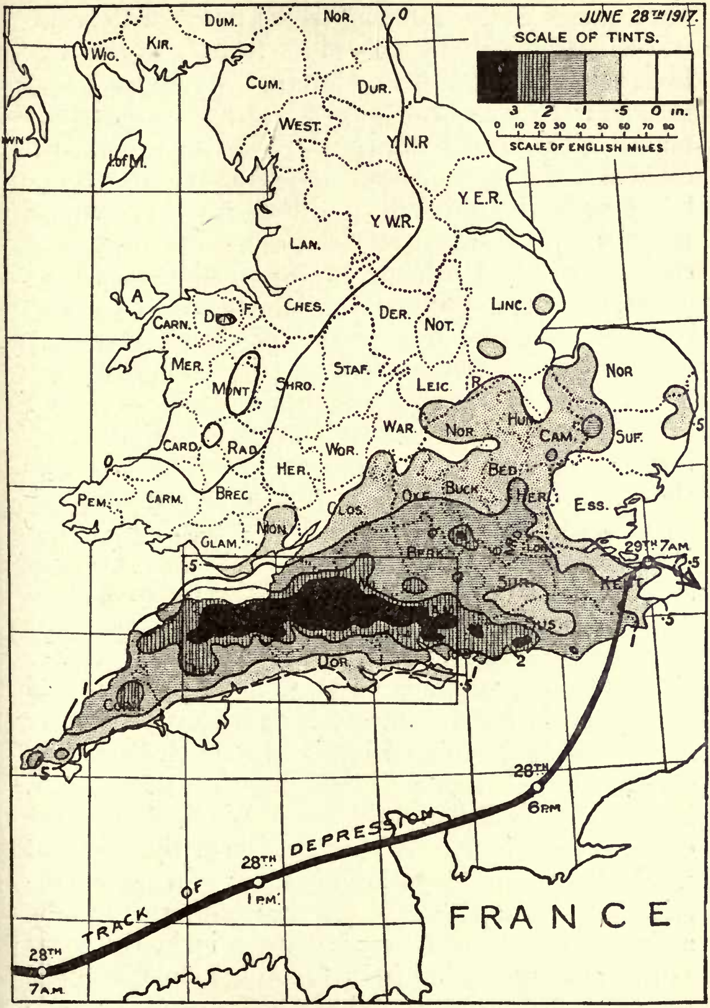


FIG. 95.—DISTRIBUTION WITH DEFLECTED CYCLONE TRACK—4.
(See also FIG. 96.)

the distance covered during the 24 hours of the rainfall day being about 350 miles from a point near Ushant to the east coast of Kent. It appears that the central area of low pressure spread, rather than moved, eastward during the day, and by 6 p.m. had divided into two distinct low-pressure areas, one lying near the original position off the coast of Brittany, the other over Belgium. Each of these centres exhibited a definite wind circulation, and by 7 a.m. they had again coalesced. On the morning of the 29th the direction of movement was abruptly modified from north-eastward to south-eastward. The exact hour at which such a change takes place in the direction of travel of a depression is usually difficult to determine accurately, but in this case the data are sufficient to justify the assumption that the time was not earlier than 7 a.m.

Apart from trivial showers in Wales, the day appears to have been rainless to the north-west of a fairly straight and extremely well-defined line from near Cardigan to Newcastle-on-Tyne. To the south-east of this line no station failed to record some rain, but less than ·25 inch fell over an outer zone roughly 50 miles wide in the north-west, and also at one or two points along the south coast, between the Lizard and the Isle of Wight, and on the east coast in Essex. Within the limits thus defined the fall increased to ·50 inch gradually on the northern side, more abruptly on the southern, and by a similar transition to more than 1 inch, the main 1-inch area stretching from St. Agnes, in Cornwall, to near Canterbury. There were one or two detached areas with 2 inches, but the only one of importance occupied 4,144 square miles and extended from Hartland, in North Devon, to a point near

RAINFALL OF JUNE 28TH 1917.

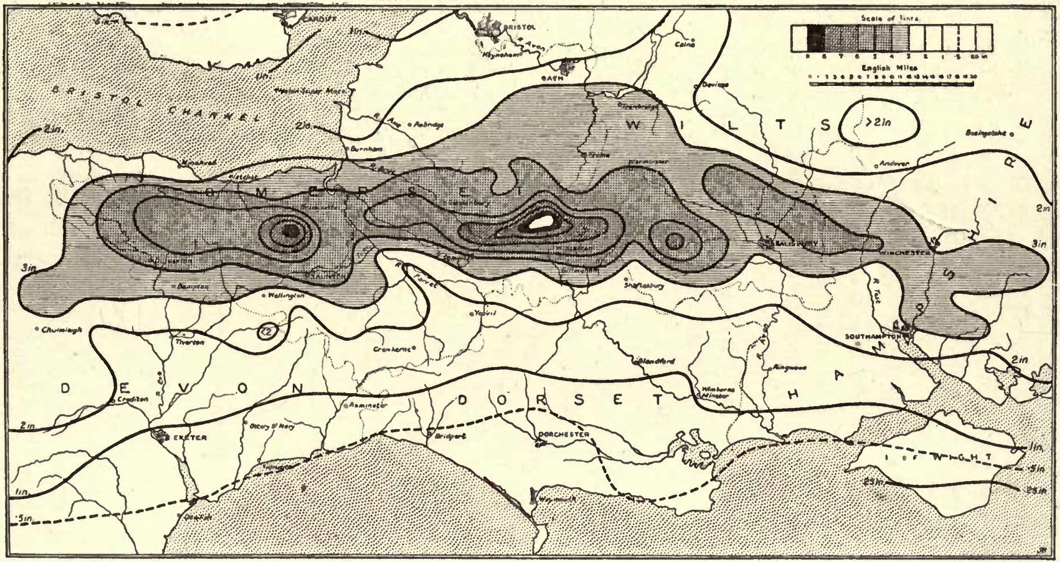


FIG. 96.—RAINFALL OF JUNE 28, 1917. DETAIL OF WETTEST AREA.

(*See also* FIG. 95.)

Brighton, being 185 miles long and 30 miles wide, and enclosed a somewhat similarly shaped area with falls exceeding 3 inches. In the map (Fig. 95) this area is shown in solid black; the details are shown on a larger scale in Fig. 96. In studying this map, attention may be drawn to the evident tendency for the splashes of heavy rainfall to be arranged in a linear manner. This is no doubt associated with the movement of the depression-centre during the 28th, being nearly parallel to it, and is probably an entirely different phenomenon to the linear arrangement noted in respect of thunderstorm-rains.

The increase of rainfall to a central axis or string of patches lying between Exmoor and Salisbury is very striking, more than 5 inches falling nearly everywhere over a strip about 70 miles long and generally not more than 6 miles wide. In two small patches within this strip there is good evidence that more than 8 inches fell, culminating in the unprecedented measurement of 9·56 inches at Bruton. The circumstances of this very remarkable rainfall were personally investigated by Dr. Mill in company with the author, and there appears to be no reason to doubt the substantial accuracy of the reading.

The very pronounced similarity between the barometric conditions at the time of the four great cyclonic rainstorms of which a brief account has been given is probably sufficient to establish the fact that some intimate connexion must exist between the phenomenon of a deflected track and the heavy rain, and that the *locale* of the latter is intimately associated with that of the former. It has been pointed out, however, that in each case the pro-

bability seems to be that the deflexion occurred, if not *after* the heavy rain, at any rate towards the end of it, and it may be that the deflexion itself is really the effect rather than the cause of the precipitation. In the present state of our knowledge it seems best to confine ourselves to putting the facts on record, in the hope that their interpretation may thereby be facilitated.

The generalizations which may safely be drawn from the study of exceptional cyclonic rainfalls appear to be that they commonly occur in a northerly or easterly current of air on the left hand of the track of the depression, and that the distribution of the heavy rain is independent of the configuration of the land. With travelling depressions there is a distinct tendency for the rain-areas to be parallel to the path of travel, this parallelism extending frequently to the zero limit of rain some hundreds of miles distant. With stationary or irregularly moving depressions, no linear arrangement is observable. The hypothesis that the moisture-laden southerly and southwesterly winds in the right-hand rear sector of the cyclone are obstructed and lifted into the upper strata on impinging on the cold easterly or northerly drift is strongly supported, and there is every reason to regard it as providing an explanation of the concentration of the heaviest falls on the left of the track, and in a region of prevailing northerly or easterly wind.

Cyclonic rainfalls, in spite of the very large amounts sometimes deposited, are never so intense as convectional rainfall. The most noteworthy instances of heavy cyclonic rain, including the great falls of August 25–26, 1912, and June 17, 1917, never appear to have yielded intensities at the rate of more

than 1 inch per hour, and in more moderate cases a rate of ·20 inch per hour would probably be quite normal. In the study of heavy thunderstorms, the number of instances of rain falling at a rate exceeding 1 inch per hour is so great that it is not usually thought necessary to put them on record. Numerous examples of convectional rainfall at rates approaching or exceeding 3 inches in an hour have been recorded, whilst for shorter periods 6 or even 10 inches per hour has been observed. A second point of difference between the two types will have been apparent from the study of the maps illustrating this chapter, namely, the much more widespread and uniform nature of the rain-areas in cyclonic than in convectional rain. In every case mentioned, and in a very large number of others which have been passed over for want of space, the number of records upon which the maps have been based has been several thousand, no large area being unrepresented, so that the outlines of the rain-fields are well established, and their homogeneity, or want of it, is not merely apparent owing to want of data. This refers to the rainless areas equally with those of rainfall.

Turning to the third great rainfall type, viz. orographical rainfall, it is necessary to bear in mind that this is so frequently associated with cyclonic rain that it is often difficult to isolate it as a type on individual days. Strictly speaking, the orographical effect is a *tendency* rather than a distinct type. It is liable to occur either by itself, or more often as a modifying influence on the cyclonic type, whenever the distribution of pressure is such as to favour wind blowing from the sea to the land. Owing to the comparatively small sea-area on the east of the British Isles and the fact that easterly

winds are cold and therefore do not conduce to much evaporation, the orographical rains from this quarter are not, as a rule, of great importance; they nevertheless do occur. The most pronounced orographical effect is found with westerly and south-westerly winds carrying large quantities of water-

Pressure distribution giving Straight Isobars.-16th Jany. 1920.

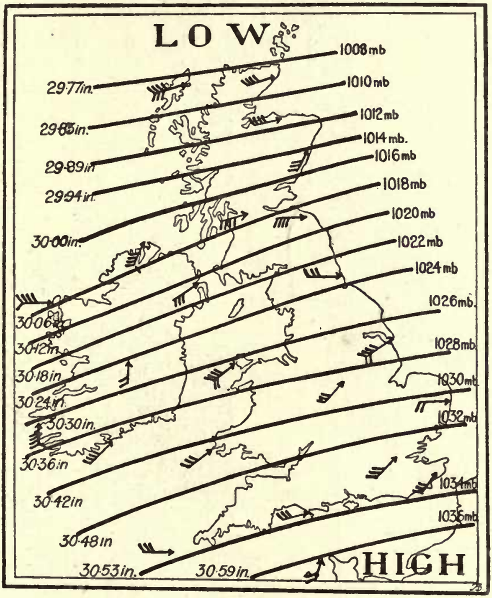


FIG. 97.—PRESSURE CONDITIONS FAVOURABLE FOR OROGRAPHICAL RAINFALL.

vapour from the Atlantic and meeting mountain barriers in their passage. Such winds blow most steadily when the lowest barometric pressure lies to the north or north-west and the isobars cross the British Isles in straight lines from south-west to north-east, as in Fig. 97.

The condition of westerly winds impinging on the

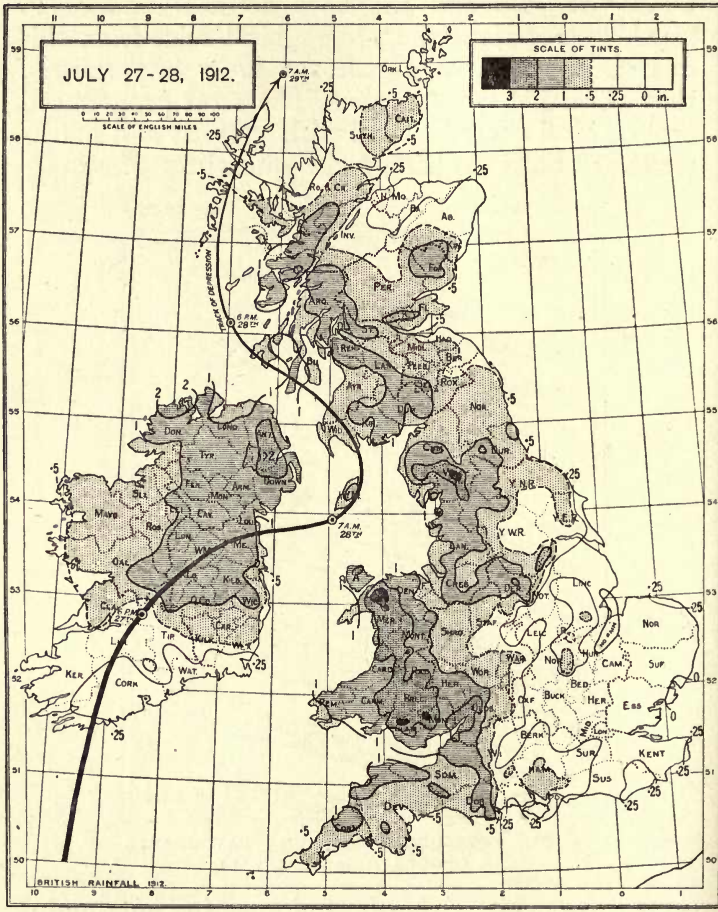


FIG. 98.—OROGRAPHICAL RAINFALL PRODUCED BY PASSAGE OF DEPRESSION.

mountain slopes may, of course, arise in connexion with the passage of a cyclone, especially if the track should lie from south to north along the west coast. An example of this is seen in Fig. 98.

Judging by the analogy of other maps, it would appear probable that the patch of heavy rain in the north-east of Ireland was of cyclonic origin, forming the usual wet area on the left of the track and accentuated within the loop where the track makes a detour eastward. This rain shows little correlation with the configuration of the land. On the right-hand side of the depression-track, where it is reasonable to suppose that the south-westerly winds blowing in its right-hand rear sector would strike the uplands of Wales, England, and Scotland, the distribution of rainfall shows a well-marked association with the orography. This is indicated by the patches of heavy rain on Exmoor, over the mountains of South and North Wales, especially on Snowdon, on the Pennines and Lake District mountains, and those of the West Highlands.

The occurrence of orographical rain over the whole western sea-board of Great Britain on the same day, as in the case of a depression moving from south to north, is unusual. With straight isobars it is more common to find that precipitation is heavy only over a tract from 100 to 200 miles wide, and that the remainder of the country is comparatively unaffected. This fact lends some weight to the hypothesis that orographical rain is dependent not entirely on the configuration, but upon some other factor differentiating one part of the broad stream of oceanic wind from another. This factor may well be a tendency to convergence of the currents in one track and to divergence in another, but the difficulty of ascertaining the precise direction of the isobars over the sea renders this uncertain.

Fig. 99 provides an example of the distribution of rainfall with straight isobars when the tendency

for precipitation is to the northward. The rain is as a rule very widespread, and where heavy is con-

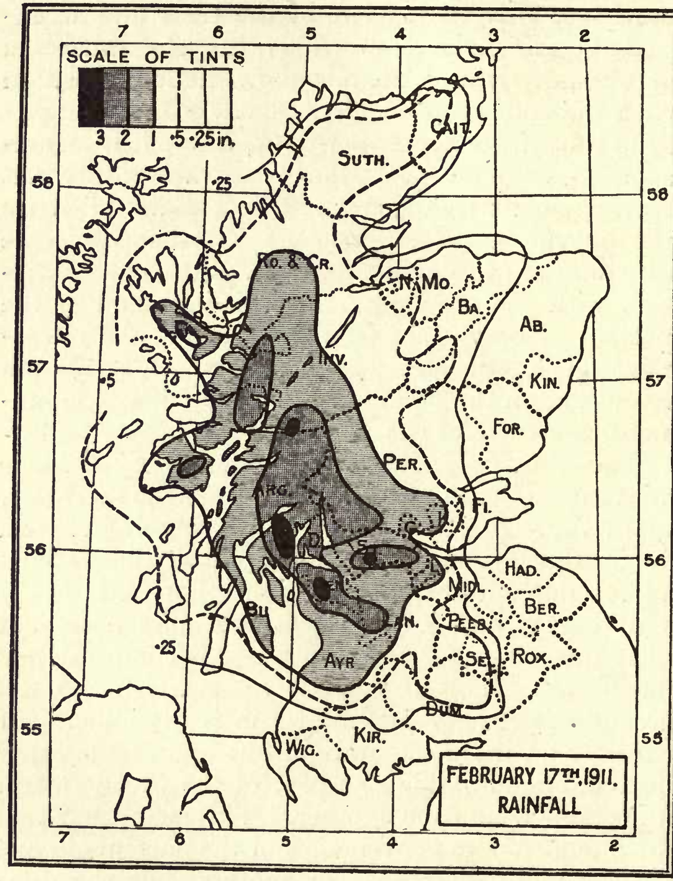


FIG. 99.—OROGRAPHICAL RAINFALL—NORTHERLY TENDENCY.

fined to the mountain areas, falling off to a minimum in the east. In the instance exemplified, there is clearly a greater tendency for rain in about latitude

56° N. than elsewhere, since the fall here is greater though the mountain barrier at this point is less lofty than farther to the north, and since the penetration of the high fall eastward is more pronounced than in any other part. It will be seen that there is a comparatively slight increase of fall over the high mountain chain of the eastern Grampians, no doubt because the air passing over the more westerly high land has been dessicated and thus deprived of its capacity to condense. The simplicity in the run of the isohyets in comparison with those for cyclonic rains may be illusory, since the smaller number of rainfall stations recording every day in mountainous regions makes it impossible to map the finer details. In mapping the rainfall of longer spells, such as months or years, when the orographical rainfall greatly preponderates, the introduction of readings for gauges measured at longer intervals invariably shows numerous sinuosities in the run of the lines.

In Fig. 100 the distribution of an orographical rain affecting a more southerly area is depicted. The main axis of intensity appears to have lain across South Wales, where the mountains of Glamorganshire and Brecon received more than 3 inches during the day. The general coincidence of the 1-inch splash with the mountain areas is unmistakable, and the rapid diminution of fall to the leeward is equally marked, less than ·25 inch being recorded in the Midlands and no rain in the east.

The difficulty of segregating typical instances of individual orographical rains makes it preferable to study the more intimate relation of the fall to configuration by means of maps of longer periods. The much greater frequency of orographical rain-

RAINFALL APRIL 26TH, 1913.

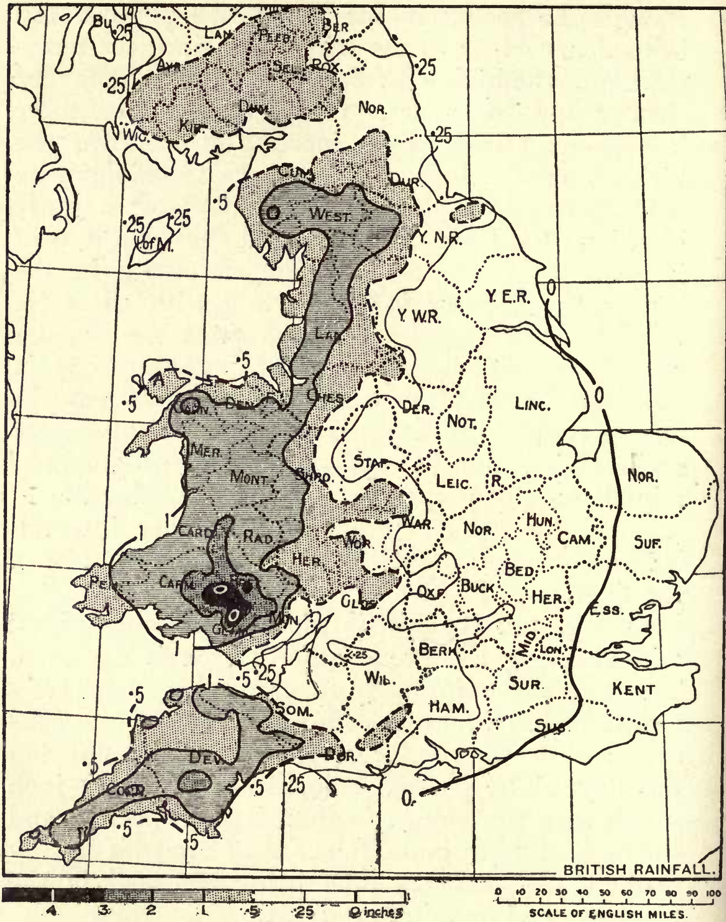


FIG. 100.—OROGRAPHICAL RAIN—SOUTHERLY TENDENCY.

fall than of other types, especially at some seasons, and the fact that they tend to be repeated in the same places, whilst convectional and cyclonic rains

occur indiscriminately over the country, results in the orographical influence being more and more strongly marked as the period dealt with is longer. A further consideration of the subject is given in Chapter XIV.

CHAPTER XII

THE SEASONAL VARIATION OF RAINFALL

The relative seasonal frequency of rainfall of different types in the British Isles has already been referred to. On account of the great and capricious fluctuations to which rainfall is liable at all seasons, the normal seasonal march may in individual years be completely masked—that is to say, although, for example, the orographical type of regional distribution is highly characteristic in the long run of the winter months, it frequently occurs in the summer, and although a completely non-orographical distribution is probably very rare in the winter, the winter type is sometimes so largely modified that it is indistinguishable from that proper to the summer.

In studying the fluctuations, both in amount and distribution, of seasonal rainfall, the most convenient unit of time is the calendar month. The period is sufficiently long to minimize the effect of most of the chance variations arising from individual thunderstorms, and sufficiently short to ensure that the individual characteristics of each season will be satisfactorily indicated. It is unfortunate for some purposes that the calendar months are of unequal length, but the inconvenience arising from this is not enough to outweigh the great advantage of dealing with a universally recognized period of time,

and one in which climatological data have always been naturally grouped.

In order to free ourselves from the disturbing effect produced by the abnormalities of individual seasons in studying the normal seasonal march of rainfall, the most suitable data are the average monthly rainfall totals for a number of years. If we were considering yearly totals, where the fluctuations are relatively much smaller, the average of 35 years would give practically constant values. In dealing with monthly totals this does not by any means hold good, and it is probable that to obtain steady values for each month at least 100 years' observations would be necessary. Very few records exist for so long a period, and any attempt to establish regional distributions would, therefore, be futile, so that all that it is possible to do at the present time is to study the averages for 35 years, with the accepted reservation that they must be regarded merely as approximating to and not necessarily representing exactly the normal seasonal variation.

For the purpose of the present chapter the averages used are in all cases, unless otherwise stated, taken from the period 1881 to 1915 inclusive. About 550 uniform sets of average monthly values for stations as nearly as possible equably distributed over the British Isles are available and have been drawn upon.

In order to obtain some idea of the magnitude of the deviation from the normal liable to arise by using so short a period as 35 years, the average values for 1881 to 1915 at Greenwich, Kendal, and Rothesay may be compared with the average for 100 years at these places. The records were not quite homogeneous throughout the century, but this probably

does not affect the results appreciably from the point of view of seasonal march.

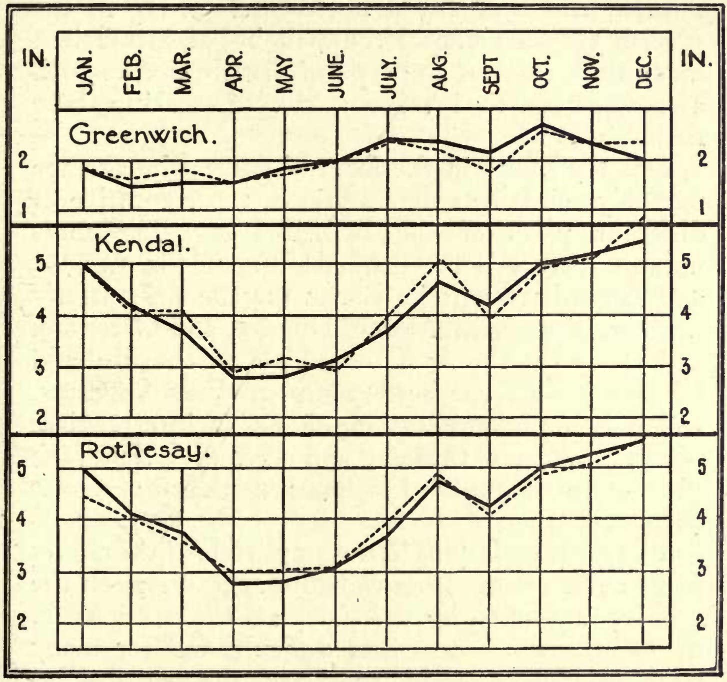
—	Greenwich (London).			Kendal (Westmorland).			Rothesay (Bute).		
	Average rainfall 100 years, 1820–1919.	Average rainfall 35 years, 1881–1915.	Average of 35 years as percentage of average of 100 years.	Average rainfall 100 years, 1820–1919.	Average rainfall 35 years, 1881–1915.	Average of 35 years as percentage of average of 100 years.	Average rainfall 100 years, 1820–1919.	Average rainfall 35 years, 1881–1915.	Average of 35 years as percentage of average of 100 years.
	in.	in.		in.	in.		in.	in.	
Jan.	1·81	1·69	93	5·08	5·04	99	4·95	4·50	91
Feb.	1·56	1·57	101	4·20	4·08	97	4·09	4·00	98
March	1·59	1·73	109	3·83	4·10	107	3·73	3·59	96
April	1·60	1·47	92	2·69	2·89	107	2·75	2·98	108
May	1·87	1·73	93	2·74	3·14	115	2·81	3·03	108
June	1·98	2·02	102	3·32	2·91	88	3·15	3·07	97
July	2·44	2·24	92	4·12	3·98	97	3·70	3·96	107
August	2·38	2·19	92	5·02	5·11	102	4·65	4·87	105
Sept.	2·15	1·79	83	4·46	3·95	89	4·24	4·05	96
Oct.	2·67	2·53	95	5·43	4·89	90	4·99	4·41	88
Nov.	2·30	2·28	99	5·21	5·10	98	5·21	5·07	97
Dec.	2·02	2·26	112	5·71	5·97	105	5·46	5·45	100
Year	24·37	23·50	96	51·81	51·16	99	49·73	48·98	98

The mean deviation of the 35-year values from the 100-year averages is 7·1 per cent. for Greenwich, 6·5 per cent. for Kendal, and 5·4 per cent. for Rothesay. Two months at Greenwich, three at Kendal, and one at Rothesay show a deviation exceeding 10 per cent., the greatest departure being 17 per cent. in September at Greenwich. The same month showed a departure of 11 per cent. at Kendal, bearing out the fact to which attention has often been called, that during the early years of the present century the rainfall of September was so frequently below the normal as to give rise to a pronounced drop in the 35-year average.

Another method of looking at the point is to examine the effect on the average of an individual

rainstorm of exceptional magnitude. Thus a summer thunderstorm yielding 3·50 inches of rain, an amount which sometimes falls in a couple of hours, increases the 35-year average of the month

Average Rainfall. 1820-1919 and 1881-1915.



1820–1919. 1881–1915.

FIG. 101.

in which it occurs by ·10 inch, and the 100-year average by ·03 inch ; and taking the most extreme case known to have been observed, the great fall of 9·56 inches in 12 hours at Bruton during the cyclonic rain of June 17, 1917, would have affected

the average of June for 35 years by ·27 inch or 12 per cent., and that of 100 years by ·10 inch or 4 per cent.

In spite of this there is reason to think that, in the main, any period of 35 years will establish a working approximation to the normal seasonal march of rainfall, and that any abnormalities arising in the special 35 years considered will be of insufficient magnitude to mask the type of distribution in such a manner as to involve a risk of making false deductions.

Fig. 102 shows in the form of curves the average monthly rainfall at nine stations, representative of different parts of the British Isles. The most notable feature is the marked difference in amount and range between the curves for the dry easterly stations, Tenterden, March, Dundee, and Greenore, and those for the west, of which Seathwaite and Glenquoich are the best examples. Fort Augustus, which is an inland station, shows an intermediate range. Between the east and west of Ireland the distinction is much less marked than in Great Britain.

The great variations in the amplitude of the curves in Fig. 102, arising from the differences between the relative amounts of the falls at the stations in question, make comparison difficult, and for many purposes it is preferable to express the averages not in units of depth but as percentages, or coefficients, of the annual total. When the data have been treated in this way, the curves appear as in Fig. 103. Attention should be given to the variations in the type of curve found for different districts. Thus in the rainy regions of the west, represented by Seathwaite, Nanthir, Glenquoich, and Enniscoe,

the wettest months are at midwinter and the driest in the early summer ; whilst in the east (Dundee and Greenore) the maximum occurs in the summer. In the south-east of England, however (March and Tenterden), the wettest month is October. The spring months are everywhere dry and the autumn months are everywhere wet. It would probably be approximately correct to regard the seasonal curve in general terms as represented by a resultant of two oscillations, one between the equinoctial and the other between the solstitial seasons. The equinoctial oscillation appears to be similar over the whole country, but to be of greatest amplitude round the coast, especially in the south. The solstitial oscillation undergoes a complete reversal from a summer maximum and winter minimum in the east to a summer minimum and winter maximum in the west.

These facts are more clearly brought out by studying the geographical distribution of the percentage coefficients for each month. Maps constructed by plotting the percentage which the average monthly rainfall forms of the annual average are termed "Isomeric," and the lines upon them "isomers," or lines indicating equal proportion.

Figs. 104 to 107 are the isomeric maps for four typical months for the period 1881 to 1915. In January, representing the winter solstice, the proportion of the year's rainfall falling is greatest in the rainy westerly uplands, pointing to a predominance of rain of the orographical type. There is a diminution in the percentage values observed towards the east, and a well-marked minimum along the east coast occurs in the districts where orographical rain is least frequent. The map provides

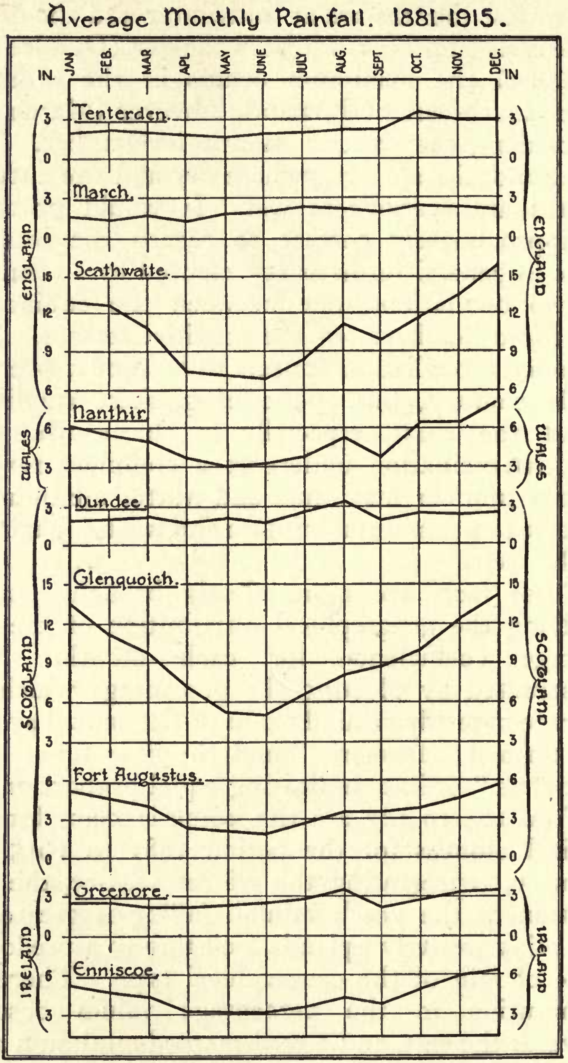

Average Monthly Rainfall. 1881-1915.
IN.
JAN
FEB.
MAR
APL
MAY
JUNE
JULY
AUG.
SEPT
OCT.
NOV.
DEC.
IN
ENGLAND
WALES
SCOTLAND
IRELAND
Tenterden.
March.
Seathwaite.
Nanthir
Dundee.
Glenquoich.
Fort Augustus.
Greenore.
Enniscoe.

FIG. 102.

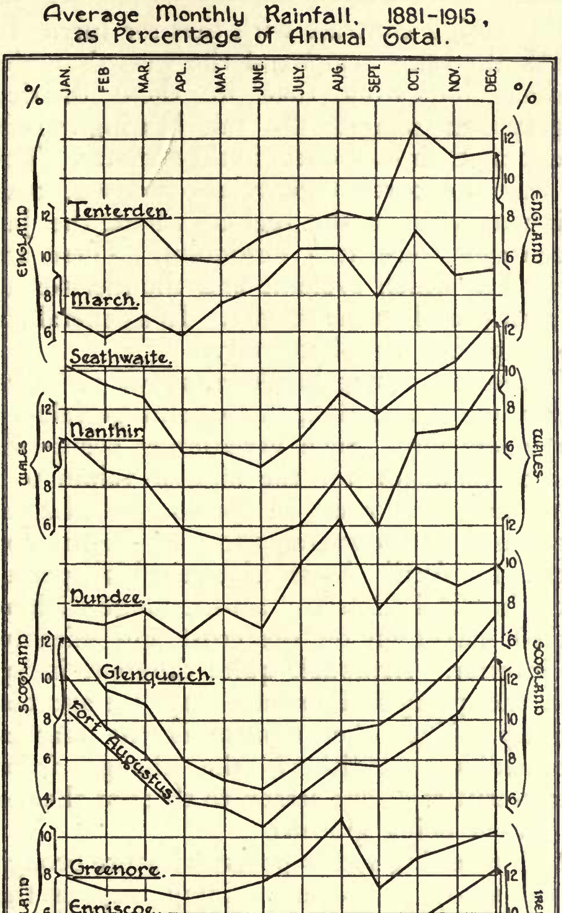

Average Monthly Rainfall. 1881-1915,
as Percentage of Annual Total.
JAN. FEB MAR. APL. MAY. JUNE. JULY. AUG. SEPT OCT. NOV. DEC.
%
ENGLAND
Tenterden.
March.
Seathwaite.
WALES
Nanthir
SCOTLAND
Dundee.
Glenquoich.
Fort Augustus.
IRELAND
Greenore.
Enniscoe.

FIG. 103.

an interesting contrast with that for July. In this month the rainy regions of the west show definite minima, indicating that in these districts of orographical rainfall the rain-bearing winds are producing their least effect in the summer. Towards the east the percentage values increase, reaching their maximum in the regions where the January percentages were at a minimum. These are the districts in which cyclonic and thunderstorm rains are most prevalent in summer. In a general way the two maps are complementary.

The isomeric map for April shows an extremely small range of variation, the percentage values being everywhere low. Such variation as occurs shows a definite tendency for the highest values to occur inland and the lowest on the coast. The autumn map, based on the averages for October, in contrast to that for April, shows relatively high percentage values in all districts and a wide range with a well-marked maximum on the coast and minimum in the interior. Although quite different in appearance, the spring and autumn maps are also complementary. The other months of the year exhibit intermediate conditions, the change from the characteristics of one season to those of the succeeding season being gradual.

An interesting and important feature brought out by the study of isomeric rainfall maps is that the distribution of percentage co-efficients, although, as the summer and winter maps clearly show, influenced by the orographical features of the country, is not definitely dependent upon the height of the ground. For example: a large group of stations lying in the West Highlands of Scotland, at greatly varying elevations and with widely

FIG. 104.

divergent amounts of rainfall, give substantially identical coefficients in each month of the year. The same characteristic is observable in other districts. On the other hand, stations with approxi-

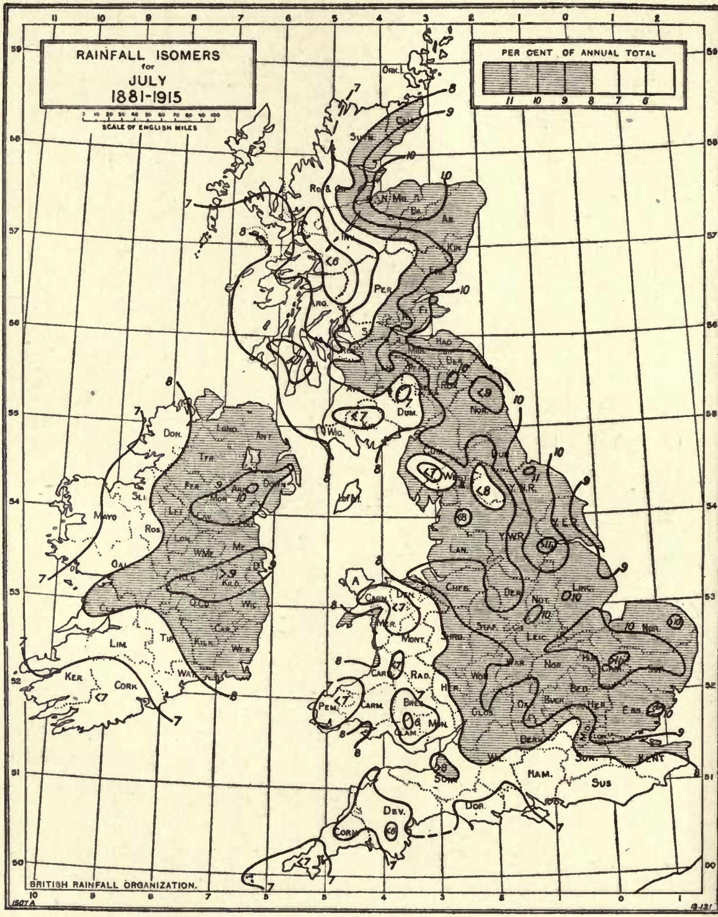


FIG. 105.

mately the same rainfall, or at the same elevations but in different geographical regions, are found to exhibit differences in the monthly coefficients of a marked nature. The identity of the values for

FIG. 106.

adjacent stations in individual months gives to the isomeric maps a simplicity of outline in contrast with the extraordinary intricacy of the detailed isohyetal lines which represent the distribution of

FIG. 107.

actual rainfall. In other words, whilst the amount of rainfall in an average year depends intimately on the detail of the configuration, the distribution of this amount between the twelve months depends upon geographical factors of a much more general kind.

Advantage has been taken of this fact to use the isomeric maps as a stage in the preparation of maps showing the distribution of average monthly rainfall. The method used was to construct a highly detailed map of the average annual rainfall (see Fig. 123) and to combine it successively with each of the monthly isomeric maps.[1] The maps thus produced give the average monthly distribution with any desired degree of detail up to that possessed by the annual map.

Figs. 108 to 111 inclusive show the regional distribution of rainfall for the period 1881–1915 in January, July, April, and October. They should be studied in conjunction with a physical map. It will be observed that at all seasons the main control is orographical, but the seasonal fluctuations of this control are conspicuous.

The contrast between the amount of rainfall in the mountainous regions and that in the plains is greatest at mid-winter. In January large areas in North Wales, the English Lake District, and especially in the West Highlands have more than 10 inches, and in the wettest regions more than 15 inches falls. The west of Ireland is not subject to so large a rainfall, and only one small area in Connemara is indicated as receiving as much as 10 inches. To the eastward, both in Ireland and Great Britain, the amount falls off rapidly, a considerable area having less than 2 inches, whilst in the Thames Estuary and part of the Fen District less than 1·50 inch falls. Thus the range of average rainfall at the season exceeds the ratio of one to ten.

[1] For a more complete description of the method employed, see *Q.J.R. Met. Soc.*, vol. xlvii, 1921, p. 101.

In July the contrast between mountain and plain, and between east and west, although clearly discernible, is at a minimum. In the West Highlands no spot appears to have as much as 10 inches, and only very small areas in Cumberland and Carnarvonshire show so great a fall. Most of the rainy area in the west of Ireland has less than 6 inches. The east, however, is wetter than in January, about 2·50 inches falling over most of the south-east of England with a minimum of about 2 inches. The absolute range for July is thus in the ratio of only about one to five.

April and October are intermediate months in respect of the contrast between the wettest and driest districts, but April is everywhere dry and October everywhere wet. It is interesting to note that the rainfall of the driest districts is approximately the same in April as in January, whilst that of the wettest districts is similar in October and January. Conversely the wettest districts in April do not differ much from the wettest in July and the driest in October from the driest in July.

In the west generally January and December are the wettest months of the year; somewhat farther east October takes their place, and in the extreme east August or sometimes July. In the case of the driest month a similar transition occurs; in the west this is June or May, changing to April or March in the more easterly districts, and in the most easterly of all to February. In nearly all parts of the country the driest and wettest months are six months apart.

There appears to be no doubt that the winter to summer fluctuations of rainfall are simply an expression of the average seasonal variation in the

FIG. 108.

intensity of the prevailing Atlantic wind-drift, which plays such an important part in moulding the climate of Western Europe, coupled with that of the prevalence of thunderstorm and purely

FIG. 109.

cyclonic rains. The spring to autumn fluctuation is not so simply explained, but there is no doubt as to its reality.

From the series of maps in question it is possible

FIG. 110.

to derive by means of the method described on pp. 100–102 a set of values of the general rainfall for the countries comprised in the United Kingdom and for the British Isles as a single unit. It will be seen

FIG. III.

that for the whole kingdom the driest month is April, though May and June are only slightly wetter, and that these three months are the only ones with a general rainfall of less than 3 inches. Similarly,

October, November, and December are the only months with more than 4 inches over the country as a whole, and of these December is the wettest. The fact that the type of the normal seasonal curve for the British Isles resembles that for a rainy district more closely than that for a dry district indicates that the orographical type predominates, a fact which is equally clear from the maps themselves.

General Rainfall, Average 1881–1915, as Computed from Isohyetal Maps

—	England.	Wales.	Scotland.	Ireland.	Isle of Man.	England and Wales.	British Isles.
Jan. .	2·69	4·72	4·90	4·07	3·17	2·99	3·78
Feb. .	2·34	3·94	4·18	3·53	3·03	2·57	3·26
March .	2·47	3·82	4·05	3·36	2·82	2·67	3·22
April .	1·98	2·96	2·99	2·75	2·30	2·12	2·52
May .	2·19	2·95	3·01	2·75	2·63	2·30	2·61
June .	2·33	3·05	2·83	2·82	2·37	2·44	2·64
July .	2·75	3·60	3·78	3·37	3·00	2·87	3·25
August	3·11	4·71	4·51	4·20	3·73	3·35	3·88
Sept. .	2·37	3·51	4·00	3·13	3·00	2·54	3·09
Oct. .	3·69	5·63	4·90	4·08	4·32	3·97	4·25
Nov. .	3·19	5·25	5·29	4·28	4·40	3·49	4·19
Dec. .	3·56	6·00	5·88	4·96	4·53	3·92	4·72
Year .	32·67	50·14	50·32	43·30	39·40	35·23	41·41

The distribution of rainfall shown by the monthly average map is of course never exactly reproduced in any individual month. It represents the amount and regional type from which, in the long run, the actual deviations are least. No instance has yet been found, in the series of monthly rainfall maps published in *British Rainfall* since 1903, in which some part of the British Isles did not exhibit a rainfall as much as 40 per cent., either in excess or

in defect, of the average amount proper to the season and place. In 108 out of the 204 months in the series some area showed a departure of 100 per cent. or more, in 21 cases there were departures of 200 per cent., and in at least one of 300 per cent., at individual stations. In the least rainy month known to have occurred, viz. February 1891, no rain fell over considerable areas in England, so that locally the range of variation of monthly rainfall may be put at not less than from 0 to 400 or possibly 500 per cent. of the average.

Out of the 204 months for which comparable data are available, the rainfall was above the average in every part of the British Isles in only two cases, March 1908 and September 1918; and below it over the whole country in three, all in September in the years 1906, 1907, and 1910. Thus in 199 cases there was a variation on both sides of the average during the same month in different parts of the country, and such a phenomenon must clearly be regarded as the normal condition. In 107 months there were departures of 50 per cent. or more on both sides of the average, and in 33 cases departures of 75 per cent. or more on both sides. Excesses of 200 per cent. or more at individual stations have occurred in every month except January, May, July, and November. The month of largest range was April and that of smallest range November.

Whilst the range of variability of monthly rainfall at individual stations is thus seen to be very wide, that over the country as a whole, whilst naturally much smaller, is still considerable. The following table gives the general percentage values for the British Isles for each month from 1903 to 1919 inclusive. The period is probably too short to cover

MONTHLY GENERAL RAINFALL FOR THE BRITISH ISLES AS PERCENTAGE OF AVERAGE

Year.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
1903	138	119	196	95	124	105	131	145	111	185	76	81
1904	117	158	89	116	123	67	92	109	81	48	68	92
1905	59	71	176	126	56	101	50	122	67	69	119	49
1906	156	117	94	68	158	77	60	85	43	140	114	92
1907	57	86	89	133	152	153	78	96	32	140	86	119
1908	82	96	156	122	104	70	96	106	118	48	64	96
1909	74	52	154	141	90	106	117	77	81	141	47	138
1910	119	170	69	131	103	109	109	141	30	76	119	126
1911	62	123	77	108	83	107	58	70	79	87	133	175
1912	118	107	167	47	80	182	112	161	57	101	94	145
1913	143	70	164	165	130	94	36	43	92	94	120	78
1914	79	160	162	81	85	68	107	88	67	56	132	180
1915	124	185	60	96	79	60	144	76	58	77	80	167
1916	107	169	102	117	143	102	82	91	65	162	130	97
1917	72	47	92	94	105	100	73	173	87	146	108	58
1918	112	138	57	72	95	60	140	84	211	101	93	128
1919	128	77	141	112	60	92	55	87	95	58	90	153

the whole range of possible variation, but it is sufficient to give a faii idea of the conditions. In 27 months out of the 204 the general rainfall was 50 per cent., or more, in excess of the average, but in only 11 months was there a deficiency of 50 per cent. The fall was as much as twice the average only once, and was never more than 70 per cent. below the average. In the particular period under consideration, September showed the greatest range, including both the driest and wettest months relatively to the average; but a general divergence from the average of 50 per cent. or more was far more frequent in February and March than at any other time of year. November showed the smallest range, and July and November were the only months which never experienced a general excess of 50 per cent.; whilst January, March, May,

and June in no case showed a deficiency of 50 per cent. One of the most remarkable features of the table is the fact that September had less than its average fall in 14 out of 17 years, this occurring in 9 consecutive years from 1909 to 1917. On the other hand, there was only one dry April from 1904 to 1911, inclusive. The longest run of consecutive dry months was 7, from May to November, 1919; and the longest run of consecutive wet months 7, from December 1915 to June 1916. The period from January to October 1903, 10 months, with only one falling to as much as 5 per cent. below the average, was, however, probably the most remarkable period of sustained high general rainfall.

Broadly speaking, wet winter months over the the country as a whole may be regarded as indicative of an abnormal tendency to orographical rains, probably brought about by an increased intensity in the great Atlantic wind-drift. Wet summer months are also sometimes due to an unseasonable prevalence of south-westerly weather, but more often to cyclonic rains, and sometimes to thunderstorms, which are, however, seldom sufficiently widespread to affect large areas. It is, therefore, possible that by examining the general rainfall of the summer and winter separately, some clue may be obtained on general lines to the fluctuations from year to year in the prevalence of rainfall of the different types. The general percentage values for the six months October to March and for the six months April to September for the last 13 years show that during this period the winter rainfalls were, relatively to the average, greater than the summer falls, suggesting that in recent years orographical rains have been more prevalent than is

normally the case. The run of eight consecutive wet winters from 1911–12 to 1918–19 is a striking

SEASONAL GENERAL RAINFALL OF THE BRITISH ISLES AS PERCENTAGE OF AVERAGE

Year.	Per cent. of average.		Year.	Per cent. of average.	
	Winter. Oct.–March.	Summer. April–Sept.		Winter. Oct.–March.	Summer. April–Sept.
1906– 7 .	97	102	1914–15 .	123	86
1907– 8 .	113	103	1915–16 .	116	97
1908– 9 .	78	97	1916–17 .	104	108
1909–10 .	114	104	1917–18 .	103	113
1910–11 .	97	82	1918–19 .	112	83
1911–12 .	131	110			
1912–13 .	120	87	Average of 13 years .	109	97
1913–14 .	111	83			

feature. The series is not long enough to show whether such sequences are abnormal.

CHAPTER XIII

THE FLUCTUATIONS OF ANNUAL RAINFALL

In studying the distribution or incidence of rainfall in days or months we are dealing with periods of time which individually have no special significance. It is true that a slightly marked diurnal range of rainfall is distinguishable, but it is so utterly swamped by the enormous variability of daily rainfall as to be meaningless in relation to individual days. The division of time into calendar months, although extremely useful in some respects for meteorological work, is purely artificial, and even if the calendar month coincided with the lunar period, which it of course does not, there would still be no reason for regarding it as a natural period from any climatological point of view. The year, on the other hand, is in every way suitable for the grouping of climatological observations, nearly all of which exhibit a pronounced annual term. It is probable that some improvement might be effected by ending the year on some date other than December 31, which has the effect of throwing parts of each winter into two separate years; but the difficulty of deciding precisely when winter ends and spring begins, and the fact that this occurs at varying times in different years and in different places, makes it impossible to hit on any precise date for terminating the climatological year which would be entirely free from disadvantages. Attempts have been made to obtain a more natural yearly period by tabulating records

from October 1 to September 30, but by far the greatest bulk of the available statistics are grouped in civil years from January 1 to December 31, and to adopt any other would be extremely inconvenient.

If the annual totals of rainfall at a large number of places for any individual year are examined, they will be found to exhibit a wide range of variation, the amount recorded at the wettest stations being sometimes nearly ten times as great as that at those of least rainfall. Generally speaking, it will be observed that the more elevated stations have a considerably larger rainfall than the low-lying ones, and further that, in the British Isles, the westerly stations are as a rule wetter than those in the east. If the total rainfall of a year is mapped, in order to study the distribution more closely, the records will thus be found to indicate a distribution of a strongly marked orographical type. If now we take the records for any other year and deal with them in the same way, the orographical type will be reproduced with only relatively minor differences in the run of the isohyets; but if the two years were dissimilar in regard to their total rainfall, the isohyets will be found to be shifted in places. In a map of the *average* annual rainfall over a number of years the run of the isohyets is very much like that in any individual year, and their positions are somewhere about midway between the extremes shown in the years of highest and lowest fall. The most extreme shifting of the isohyets in individual years from their average positions will not necessarily occur in all parts of the map in the same years—that is to say, the greatest departures from average conditions may occur in one district in one year and in another district in another year.

Although the variations from place to place are considerable, the departures from the average at any one place in the most extreme years appear to have definite limits. The most convenient way of studying these departures is to express the total rainfall of each year as a percentage of the average annual fall at the station. There are few completely trustworthy records extending back beyond about 1860, and as examples of the annual fluctuations since that date we may examine four long records, selected to represent different parts of the British Isles. These are at London; Haverfordwest, in Pembrokeshire; Glengyle, near the head of Loch Katrine on the borders of Perthshire and Stirlingshire; and Belfast. The four are thus situated respectively in England, Wales, Scotland, and Ireland.

Year.	London.		Haverfordwest (Pembrokeshire).		Glengyle (Perthshire).		Belfast (Antrim).		Year.
	Annual rainfall.	Per cent. of average.	Annual rainfall.	Per cent. of average.	Annual rainfall.	Per cent. of average.	Annual rainfall.	Per cent. of average.	
	in.		in.		in.		in.		
1860	32·24	126	56·99	119	94·20	103	38·23	111	1860
1861	22·27	87	51·80	108	112·50	122	34·02	98	1861
1862	27·57	108	38·30	80	105·10	114	39·18	113	1862
1863	21·59	84	45·13	94	105·50	115	36·92	107	1863
1864	16·93	66	40·06	83	80·60	88	29·49	85	1864
1865	29·48	115	50·77	106	72·20	79	32·02	93	1865
1866	31·60	124	54·97	114	100·70	110	35·56	103	1866
1867	26·29	103	55·87	116	98·90	108	32·68	95	1867
1868	23·40	91	56·01	117	118·30	129	31·58	91	1868
1869	25·42	99	54·69	114	91·00	99	32·57	94	1869
1870	21·32	83	40·01	83	71·30	77	30·14	87	1870
1871	25·02	98	46·73	97	90·10	98	31·91	92	1871
1872	33·86	132	69·78	145	127·80	139	44·46	129	1872
1873	22·67	89	45·67	95	95·60	104	31·13	90	1873
1874	18·82	74	51·15	106	106·60	116	34·78	101	1874
1875	28·44	111	58·43	122	91·20	99	31·98	93	1875
1876	26·16	102	53·49	111	93·70	102	39·89	116	1876
1877	28·17	110	64·18	134	128·50	140	42·28	122	1877
1878	34·08	133	54·05	113	82·00	89	29·14	84	1878
1879	33·82	132	49·69	103	87·00	95	33·52	97	1879
1880	30·28	118	40·76	85	69·00	75	28·76	83	1880
1881	27·92	109	45·18	94	80·00	87	38·47	111	1881
1882	27·14	106	63·39	132	104·90	114	39·32	114	1882

Year.	London. Annual rainfall.	London. Per cent. of average.	Haverfordwest (Pembrokeshire). Annual rainfall.	Haverfordwest (Pembrokeshire). Per cent. of average.	Glengyle (Perthshire). Annual rainfall.	Glengyle (Perthshire). Per cent. of average.	Belfast (Antrim). Annual rainfall.	Belfast (Antrim). Per cent. of average.	Year.
	in.		in.		in.		in.		
1883	24·40	95	50·75	106	100·60	110	33·96	98	1883
1884	20·35	80	43·60	91	107·40	117	33·28	96	1884
1885	26·64	104	50·27	105	84·10	92	29·57	86	1885
1886	27·01	106	57·64	120	81·10	88	36·88	107	1886
1887	19·21	75	35·23	73	67·00	73	23·45	68	1887
1888	27·74	109	47·08	98	89·40	97	32·80	95	1888
1889	23·85	93	37·31	77	76·30	83	31·20	90	1889
1890	21·23	83	42·82	89	95·10	104	32·58	94	1890
1891	28·15	110	51·13	106	94·40	103	31·88	92	1891
1892	22·61	88	37·45	78	89·60	98	31·21	90	1892
1893	19·80	77	35·55	74	91·90	100	25·92	75	1893
1894	27·94	109	49·75	104	101·70	111	31·63	91	1894
1895	21·47	84	38·79	81	74·20	81	33·01	96	1895
1896	23·52	92	40·69	85	76·20	83	32·83	95	1896
1897	22·86	89	50·98	106	96·10	105	35·73	103	1897
1898	17·69	69	42·56	88	112·20	122	30·26	88	1898
1899	22·54	88	42·26	88	106·20	116	34·91	101	1899
1900	23·28	91	50·06	104	104·00	113	40·56	117	1900
1901	22·17	87	45·50	95	76·70	83	32·10	93	1901
1902	20·84	81	40·72	84	65·90	72	30·41	88	1902
1903	38·10	149	56·69	118	129·50	141	42·34	123	1903
1904	20·65	81	42·72	89	88·80	97	31·84	92	1904
1905	22·97	90	39·23	83	77·10	84	31·80	92	1905
1906	24·26	95	50·40	105	81·70	89	36·15	104	1906
1907	23·01	90	44·17	92	85·10	93	38·04	110	1907
1908	23·67	92	44·91	93	88·10	96	38·75	112	1908
1909	26·75	105	41·04	85	75·70	82	36·88	107	1909
1910	25·36	99	45·61	95	88·80	97	40·57	117	1910
1911	24·79	97	49·83	104	94·80	103	35·70	103	1911
1912	27·88	109	56·59	118	106·60	116	44·43	129	1912
1913	22·41	88	53·16	111	84·00	91	37·68	109	1913
1914	25·72	101	50·53	105	95·80	104	34·98	101	1914
1915	32·18	126	49·27	103	75·40	82	36·63	106	1915
1916	34·01	133	43·33	91	96·85	105	37·60	109	1916
1917	30·04	117	41·84	87	76·25	83	36·00	104	1917
1918	29·69	116	52·49	109	96·35	105	37·99	110	1918
1919	26·21	102	42·99	89	72·85	79	34·64	100	1919
Average, 1860–1919	25·59	100	48·03	100	91·84	100	34·57	100	Average 1860–1919
Wettest year	38·10 (1903)	149 (1903)	69·78 (1872)	145 (1872)	129·50 (1903)	141 (1903)	44·46 (1872)	129 {1872 1912}	Wettest year
Driest year	16·93 (1864)	66 (1864)	35·23 (1887)	73 (1887)	65·90 (1902)	72 (1902)	23·45 (1887)	68 (1887)	Driest year
Mean deviation	± 3·62	± 14	± 6·12	± 13	± 11·95	± 13	± 3·43	± 10	Mean deviation

Fig. 112 shows the percentage variations in the form of curves. Apart from certain prominent characteristics, such as the high rainfall of 1872 and

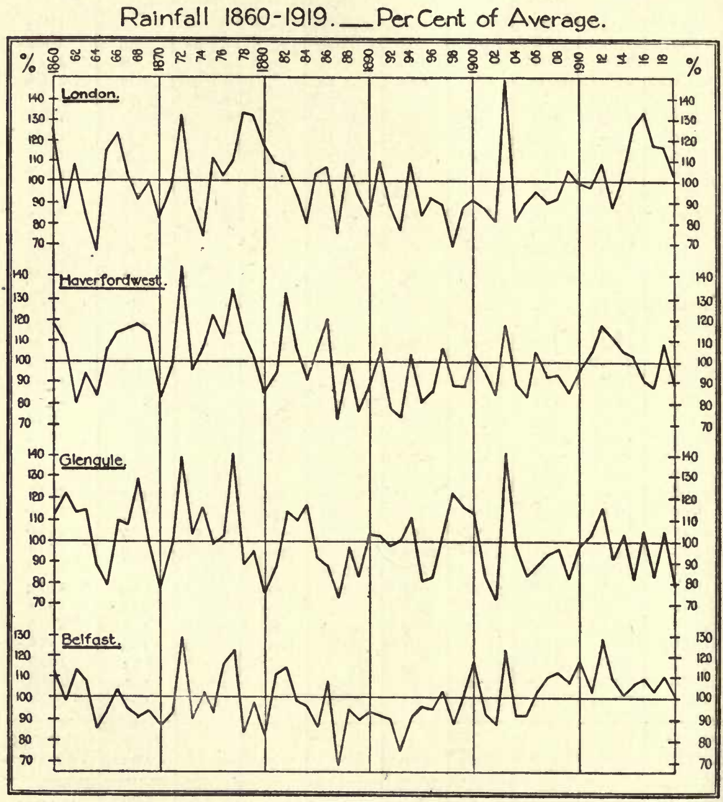


FIG. 112.

1903 and the low rainfall of 1887, which are common to all the curves, it is not easy to detect any definite similarity, beyond the fact that the range of variation at all four stations is of the same order of

magnitude. The above table shows that the mean deviation is greatest, 14 per cent., in London, but that it is only 1 per cent. smaller at Haverfordwest and Glengyle. At Belfast, however, it falls to 10 per cent. This small range is a characteristic common to all Irish stations. The extreme range is 83 per cent. for London, the wettest year having $2\frac{1}{4}$ times as much rain as the driest; 72 per cent. and 69 per cent. respectively at Haverfordwest and Glengyle, where the wettest year had approximately twice as much rain as the driest; and 61 per cent. at Belfast, where there was rather less difference between the extreme years. These values represent the range of annual rainfall in the British Isles generally.

Another way of examining the variation factor is to group the annual departures in order of magnitude.

Departures from average.	London.	Haver-fordwest.	Glengyle.	Belfast.
Per cent.	No. of years.	No. of years.	No. of years.	No. of years.
0 to 9 . . .	26	26	24	37
10 to 19 . .	21	25	24	17
20 to 29 . .	6	6	9	5
30 to 39 . .	6	2	1	1
40 or more . .	1	1	2	0

It will be observed that departures exceeding 30 per cent. of the annual average occur with greater frequency in London than at the other stations, and that departures of 10 per cent. or more are far more rare in Ireland than elsewhere.

These data illustrate the generalization that, broadly speaking, the percentage range of annual rainfall rises to a maximum in the east and falls to a minimum in the west, but that in Great Britain the

regional difference is not pronounced. The variation is probably a measure of the insularity of the climate, since in continental climates, where orographical rain is not so frequent as it is on the western sea-board of Europe, the annual rainfall exhibits a considerably wider range.

Although at first glance the curves in Fig. 112 suggest that the variations from year to year are entirely capricious, a closer scrutiny shows certain broad tendencies overlying the incidental irregularities. For example, in the curves for London and Haverfordwest the earlier years of the period considered were distinctly wetter than the later years, though there is some indication of a recovery during the last decade. At Glengyle the alternation is less marked, but still apparent, and at Belfast the wet years are more pronounced in the last two decades than at any other period, though the wet spell in the seventies common to all the curves is clearly shown.

The evidence for a long-period alternation of relatively high and low rainfall is much more conspicuously demonstrated if, instead of plotting the annual percentages, the values are expressed as successive overlapping ten-year averages, thus smoothing out minor or short-period fluctuations. This is done in Fig. 113. Here the curves exhibit a definite alternation, the rainfall rising to a maximum in about 1875, falling to a minimum in about 1890, and afterwards rising to a second maximum at the end of the period. The four curves do not precisely synchronize, and that for Glengyle is less definite than the other three, this station showing some indication of a shorter term, but all show the same tendency for alternate spells of preponderat-

ingly wet and dry years. It is interesting to observe in passing that the abnormally wet year 1903, common to all the curves, and indeed common to the whole of the British Isles, fell in a period of general dryness. Whatever, therefore, may have been the cause of the unusually great fall in this year, it was apparently not a phase of any long-period fluctuation, but a strongly marked exception to the general tendency prevailing at the time. The year

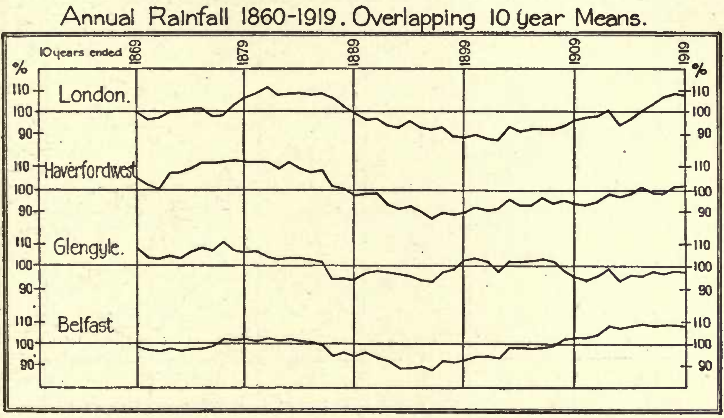


FIG. 113.

1887, on the other hand, the year of lowest rainfall over the country generally, was merely the driest of a long spell of years of deficient fall, and 1872 was the most conspicuous of a run of wet years (see Fig. 112).

The alternation of wet and dry spells is even more markedly brought out by the use of the method of "residual mass curves" suggested by Mr. A. A. Barnes[1] for the analysis of rainfall records. The residual mass curve is constructed by plotting

[1] See *Q.J.R. Met. Soc.*, vol. xlv, 1919, p. 209.

the percentage departure from the average as a cumulative value from the beginning to the end of the series. Thus the year 1860 for London had a

Rainfall 1860-1919.—Per Cent of Average. Residual Mass Curves.

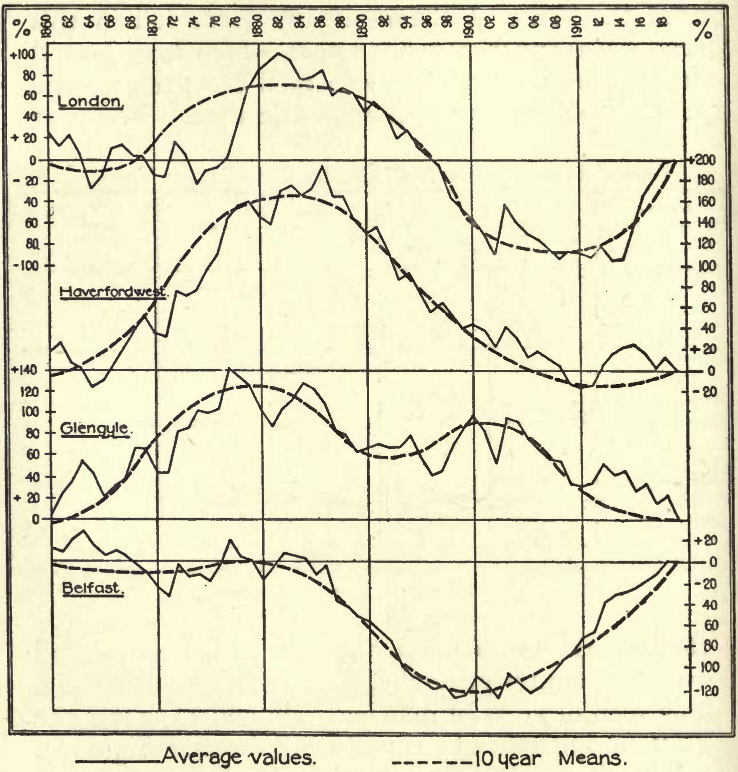


FIG. 114.

rainfall 26 per cent. in excess of the average of the 60 years and the following year a deficiency of 13 per cent., the two years taken together thus exceeding the average by 13 per cent.; the third year of the

series, 1862, had 8 per cent. above the average, and the aggregate departure for the three years was therefore 21 per cent. Continuing this process throughout the whole period, we get the curves shown in Fig. 114. The smooth lines in the same diagram represent the residual mass curves of the successive ten-year totals 1860–69, 1870–79, etc. They serve to bring out the general tendency more readily than do the crude annual curves.

The position of the curves relatively to the zero, or average line, obviously depends upon the accident of the relative wetness or dryness of the earliest years, and may, therefore, be disregarded. The important point to notice is the effect of the preponderatingly wet years in producing a tendency for the curve to rise and of the preponderatingly dry years in causing it to fall. In London, for instance, the eight years 1875 to 1882, inclusive, had an aggregate excess of 121 per cent., or 15 per cent. per annum, whereas the 20 years 1883 to 1902 had an aggregate deficiency of 190 per cent., or 9·5 per cent. per annum. The recovery from 1914 to 1919, with an aggregate excess of 93 per cent., or 15·5 per cent. per annum, is well shown.

At Haverfordwest the contrast between the wet and dry spells is still more striking. From 1865 to 1886 the aggregate excess was 209 per cent., or 10 per cent. per annum, and from 1887 to 1910 the aggregate deficiency amounted to the same total, 209 per cent., or 9 per cent. per annum. The peak of the curve at Haverfordwest is four years later than in London, whilst at Glengyle there is a double peak in 1877 and 1884, a less pronounced fall, and no recovery at the end. The Belfast curve is somewhat indefinite as to the precise date of the

maximum, and the minimum is much earlier than at the other stations. The run of dry years from 1882 to 1893 and the run of wet years from 1905 to 1919 are very well marked.

The relative values given for the individual years and groups of years of course depend for their magnitude upon the average of the whole period of sixty years considered. It would appear to be a justifiable assumption that some agency is operating to cause a periodic fluctuation in the rainfall, and although the time available for observation is too short to enable a definite term to be fixed, the data appear to indicate that during the sixty years 1860 to 1919 at least one crest and one trough are included. In all probability the amplitude and term of the fluctuation varies in different parts of the country and the epochs of maximum and minimum also probably vary in different places, though in very broad outline there is some tendency for a similarity in the type of fluctuation in all parts.

We have no evidence at present to show with any certainty whether similar fluctuations have occurred in previous years, nor whether, if they occurred, their amplitude and term were the same as here shown.

The consideration of this fluctuation is of great importance in selecting a suitable period for computing normal annual rainfall values. It has been shown that an average of 10 years may exhibit an excess or defect of as much as 12 per cent.; and even if the period be as much as 50 or 60 years, should it be chosen so as to include two maxima and only one minimum, the average will be higher than the true normal, and if two minima and only one maximum are included it will be too low. If the term

of the fluctuation can be fixed, it is not improbable that the average for some shorter period may be hit upon which will, by including only one maximum and one minimum, be closer to the normal than the average of the whole period. Sir Alexander Binnie[1] and others have examined this point with great detail and have concluded that, broadly speaking, the average of 35 years will in nearly every case represent the true normal rainfall at least as closely as any longer period for which trustworthy observations are likely to be available. It is possible to test the accuracy of this assumption conclusively only if two successive periods of 35 years can be compared, and there are certainly too few completely trustworthy rainfall records of 70 years' duration to enable this to be done. It is not without value, however, to examine the 26 successive overlapping periods of 35 years which occur within the 60 years 1860 to 1919 in their relation to the average of the whole period.

The table on page 224 shows that by far the greatest number of 35-year periods had average values below that of the 60 years, a result which would be compatible with the suggestion made above that these 60 years include two wet spells and only one dry spell, and, therefore, presumably show too large an average. The hypothesis of a constant value for 35 years is, however, shaken by the considerable range shown, the extremes differing by as much as 8 per cent. at Haverfordwest. This range is not appreciably affected by the question of the proximity of the 60-year average to the normal.

The percentage values in the table refer of course to individual stations. There is little doubt that a

[1] *Rainfall, Reservoirs, and Water-supply*, by Sir A. R. Binnie.

OVERLAPPING 35-YEAR AVERAGES AS PERCENTAGES OF AVERAGE OF 60 YEARS, 1860—1919

Period.	London.	Haverford-west.	Glengyle.	Belfast.
1860—1894 . .	101	103	102	97
1861—1895 . .	100	102	102	96
1862—1896 . .	100	101	100	96
1863—1897 . .	99	102	100	96
1864—1898 . .	99	101	100	96
1865—1899 . .	99	102	101	96
1866—1900 . .	99	102	102	96
1867—1901 . .	98	101	101	96
1868—1902 . .	97	100	100	96
1869—1903 . .	99	100	101	98
1870—1904 . .	98	99	101	97
1871—1905 . .	98	99	101	97
1872—1906 . .	98	100	101	98
1873—1907 . .	97	98	99	97
1874—1908 . .	97	98	99	98
1875—1909 . .	98	97	98	98
1876—1910 . .	98	97	98	98
1877—1911 . .	98	96	98	98
1878—1912 . .	98	96	97	98
1879—1913 . .	96	96	97	99
1880—1914 . .	95	96	98	99
1881—1915 . .	96	97	98	100
1882—1916 . .	96	96	98	100
1883—1917 . .	97	95	98	99
1884—1918 . .	97	95	97	100
1885—1919 . .	98	95	96	100
Mean value . .	98	99	99	98
Extreme range .	6	8	6	4

smaller range would be found if general values for areas were considered, and, speaking from general experience, to say that there is a range of about 6 per cent. between the largest and smallest 35-year averages which have occurred within the range of observation would probably be a fairly accurate statement. This may presumably be interpreted to mean that the average of any period of 35 years is not likely to differ from the true normal by more than 3 per cent. The wide adoption of the period

of 35 years as a basis for computing average rainfalls makes this range of variation a matter of some moment, and it must also not be overlooked that all rainfall measurements are only approximations to the true fall, and the limit of ordinary observational error, even under the most favourable circumstances, can hardly be put at less than about 3 per cent. In other words, if our inference is justified, the average of any period of 35 years will represent the true normal fall within the limits of observational error.

As has been mentioned, the range of variation of annual rainfall is perceptibly reduced if, instead of dealing with individual stations, it is possible to refer to the general values for any large area. This is of course due to the fact that the extreme measurements do not occur simultaneously in all parts of the area, and thus the larger the area the more limited will the fluctuations be. For the purpose of demonstrating this we may examine the general rainfall for the whole of Ireland, arrived at by meaning a large number of interpolated values of annual rainfall from maps for the years 1865 to 1919 inclusive. There are unfortunately not sufficient data to carry the series back to 1860, but the average of the 55 years is probably within about 0·2 per cent. of that for the 60 years, so that the difference is immaterial. The table on p. 226 gives the general rainfall for each year and the percentage which it bears to the average.

The mean deviation will be seen to be no more than 6·4 per cent. or about half that for an individual locality, and the extreme range only 47 per cent. The deviation from the average was less than 5 per cent. in 26 years and less than 10 per cent. in 43 years, reaching 20 per cent. only three times during the 55 years.

GENERAL RAINFALL IN IRELAND, 1865—1919

Year.	Rainfall.	Per cent.	Year.	Rainfall.	Per cent.	Year.	Rainfall.	Per cent.
1865	43·1	99	1883	47·0	107	1901	42·4	97
1866	44·3	101	1884	43·2	99	1902	39·1	89
1867	41·9	96	1885	41·3	94	1903	54·4	124
1868	44·8	102	1886	48·2	110	1904	44·4	101
1869	42·8	98	1887	33·7	77	1905	37·5	86
1870	39·3	90	1888	42·6	97	1906	41·0	94
1871	43·0	98	1889	41·5	95	1907	44·2	101
1872	54·4	124	1890	42·9	98	1908	43·5	99
1873	41·2	94	1891	43·2	99	1909	40·4	92
1874	43·1	99	1892	43·4	99	1910	47·4	108
1875	42·4	97	1893	37·3	85	1911	42·5	97
1876	46·5	106	1894	45·8	105	1912	45·8	105
1877	51·9	119	1895	42·0	96	1913	45·3	104
1878	41·7	95	1896	41·7	95	1914	45·4	104
1879	41·3	94	1897	47·8	109	1915	42·9	98
1880	40·9	94	1898	43·3	99	1916	47·5	109
1881	44·3	101	1899	44·1	101	1917	42·1	96
1882	49·6	113	1900	48·8	112	1918	47·6	109
						1919	39·2	90

Average 1865—1919, 43·8 inches.
Wettest years, 1872 and 1903, 54·4 inches or 124 per cent.
Driest year, 1887, 33·7 inches or 77 per cent.
Mean deviation, 2·8 inches or 6·4 per cent.

General Rainfall of Ireland.—Percentage of Average.1865-1919.

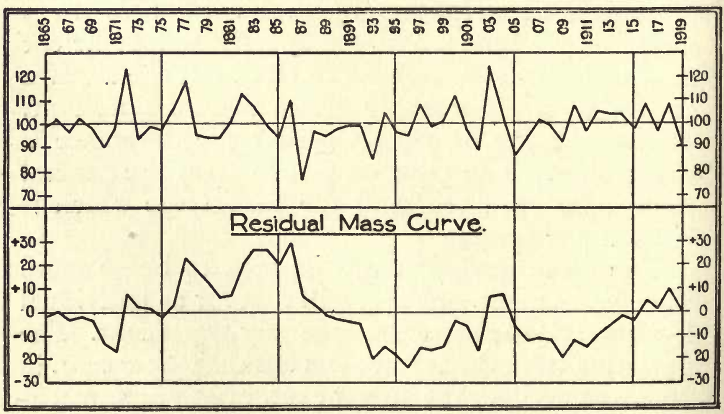


FIG. 115.

Taking the overlapping decadal means, the wettest period is from 1868 to 1877 with 102·7 per cent. of the average, and the driest, 1887 to 1896, with 94·6 per cent., the extreme range being thus 8·1 per cent. Of the 46 decadal means included in the period, 30 showed values within 2 per cent. of the average; and the 17 overlapping 35-year averages were all within 1 per cent. of that for the whole period.

The range of rainfall is certainly smaller in Ireland than in Great Britain, and the above generalizations must not, therefore, be applied to England or Scotland, but it is nevertheless certain that the general values for these countries would show much smaller variations than are found at individual stations.

Reverting to the table on pp. 214–215, attention may be drawn to the regular sequence of one wet year following two dry years at Haverfordwest throughout the twenty years 1889 to 1908. No such tendency is apparent at the other three stations, but nevertheless this temporary periodical recurrence was sufficiently widespread in England and Wales to be reflected in the general percentage of the average for the whole country from 1889 to 1909, as has been pointed out by Dr. H. R. Mill in *British Rainfall.*

England and Wales. General Percentage of Average Illustrating Three-Year Periodicity

1889	92	1896	91	1903	*129*
1890	89	1897	*101*	1904	89
1891	*110*	1898	87	1905	85
1892	89	1899	93	1906	*101*
1893	83	1900	*107*	1907	99
1894	*106*	1901	88	1908	90
1895	92	1902	83	1909	*104*

This sequence, so far as the general values for England and Wales indicate, was not apparent before 1889 and entirely broke down after 1909, but its reality between those two dates is beyond doubt. Mr. A. P. Jenkin[1] has pointed out that there is some evidence for the existence of a three-year period in rainfall over the whole of Europe, but that at intervals the order of the sequence is reversed, one dry year alternating with two wet years. He does not consider that the periodicity is confined to the twenty years commented on by Dr. Mill, though there can be no question, as far as England and Wales are concerned, that its existence was very much more marked at this time than any other. Probabably a period of a fraction less or more than three years would be found to carry the sequence further, the 21 years being the phase of apparent coincidence, and if this is the case the phenomenon should sooner or later be repeated. It is attractive to regard the period as likely to prove one-third of the sunspot cycle.

Other real or apparent sequences in rainfall records have been pointed out from time to time, and the number of different periods in which recurrences have been observed is extraordinarily large, varying from a few weeks to 41 years.[2] For the most part they have proved to be either temporary or local.

The problem of detecting and measuring weather recurrences is now being attacked in a systematic

[1] See *Q.J.R. Met. Soc.*, vol. xxxix, p. 29.

[2] For further particulars of work on this fascinating subject, the reader is referred to a series of papers by Professor H. H. Turner, F.R.S. (see *Q.J.R. Met. Soc.*, vol. xxxvii, p. 209; vol. xli, p. 315; vol. xlii, p. 163).

manner by harmonic analysis with Schuster's periodigram, a method which yields results of the utmost interest. It is to be noted that in cases where periodicities have been established their utility in foreseeing the future is limited by the fact that their occurrence is of too general a character to be applied with certainty to individual localities or definite epochs. The principal value of this line of research is to link up meteorological events or sequences with collateral extra-terrestrial phenomena, by which means a knowledge may be gained of their relationships, if any. One of these extra-terrestrial phenomena to which attention has been given is the sunspot cycle, as suggested on p. 228. Prof. Turner has recently pointed out also that there is a well-marked correlation between rainfall and temperature variations and the periodical movements of the earth's axis.

With more especial reference to the rainfall of the British Isles, a method of approaching the subject of annual rainfall fluctuations which has not yet received the attention it appears to merit is that of concentrating rather upon the distribution than upon the general excess or deficiency of the fall. Since 1906 maps have been published annually in *British Rainfall* showing the regional distribution of each year's rainfall as a percentage of the average. The data from which similar maps might be constructed for earlier years are available. The first and most striking fact which appears from the examination of these maps and data is that it is extremely rare for the total rainfall of any year to be above or below the average in all parts of the country at the same time. In most years some districts exhibit pronounced excess and others

pronounced defect, and in every year the geographical range of the deviation is of the order of 30 or 40 per cent. of the average. The distribution of the deviation is sometimes of great interest. In some years it indicates a general excess in the west and deficiency in the east, suggesting an unusual prevalence of orographical rain. In these years the winter months will be found to have been wetter relatively to the average than the summer months. In other years the rainfall will be found to have exceeded the average by a wider percentage margin in the east than the west, this excess having occurred principally in the summer. These are obviously years with a relative excess of cyclonic or thunderstorm rain. In two years exhibiting these contrasted conditions the general rainfall may be the same, whereas the circumstances which determined it were obviously different.

A point of great interest which has been observed in studying these annual percentage maps is the frequency with which parallel belts of relatively high rainfall occur separated by tracts of relatively low fall. These belts invariably extend from southwest to north-east, i.e. in a direction parallel to the track of the prevailing rain-bearing winds. It is clear that they represent the lines of highest frequency of low-pressure systems or the predominating lines of convergence in the air-drift. Wet belts occasionally occur in the same localities in several successive years, giving rise locally to runs of high annual values, but more often they shift somewhat in position from year to year.

The result of these geographical variations in the *locale* of high rainfall is to introduce an irregularity of incidence into the sequence of values for an

individual station which effectually masks any periodicity which may be in operation.

The method of research which the above considerations suggest can only be successfully prosecuted, on the lines hitherto attempted, if a large and well-distributed set of records of rainfall can be referred to, covering a period sufficiently long to yield trustworthy and comparable average values, and until recent years the number available was inadequate. When this has been improved and the number of years extended, further generalizations should be possible which will point the way to the next stage. It appears, however, already to have been established that any investigation which aims at the elucidation of the causes of the periodical rainfall fluctuations of the British Isles must primarily involve an inquiry into the causes which operate to bring about variations in the intensity and position of the North Atlantic wind-drift and of the general atmospheric circulations of which it forms a component part.

CHAPTER XIV

THE RELATION OF RAINFALL TO CONFIGURATION

Almost the first broad generalization which emerged from the systematic study of rainfall observations, and one which indeed might almost be said to have been formulated before it could be confirmed by scientific observation, so obvious was it, was that, as a general rule the amount of precipitation increases with elevation above sea-level. This statement has been found to hold good, though with some important modifications and exceptions, for all parts of the world, and it is true in a very special sense for the British Isles. Coming to closer quarters with the problem, however, it soon becomes evident that, although in the long run the relationship between land elevation and rainfall almost always exists, its numerical expression is not always the same. With close study the apparent exceptions and anomalies prove, as is invariably the case with natural phenomena, to throw more light on the true nature of the problem than the instances which follow the rule.

It will be clear from the preceding chapters that on any individual day almost any conceivable rainfall distribution may occur, and the orographical features of the land surface may or may not have any association with it. It is only when longer periods are dealt with that the relative frequency of the

different types begins to tell. Since 1908 there have been published in *British Rainfall*, maps showing the distribution of the total rainfall of each month over the British Isles. A cursory examination of each map is sufficient to indicate whether on the whole the rainfall distribution was dictated by the land configuration or not, that is, whether the orographical rains predominated over the convectional and cyclonic rainfalls in combination. In a large number of cases there is quite distinct evidence of the occurrence of considerable orographical rain during the month, but insufficient to make it the dominating factor in the distribution. In the following summary these cases are placed in a separate class :

Classification of Monthly Rainfall Distribution, 1908-1919

—	Number of instances.											
	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.
Well-marked orographical influence	12	11	10	10	4	6	2	9	7	6	12	12
Slightly-marked orographical influence	0	1	1	1	7	4	10	3	4	5	0	0
No apparent orographical influence	0	0	1	1	1	2	0	0	1	1	0	0

It should be noted, in the first place, that in the four winter months, January, February, November, and December, well-marked orographical influence occurred on all but one occasion. These months form the period when south-westerly winds are at their greatest frequency and greatest average velocity. Convectional rains are probably completely absent, and cyclonic rains, though not infrequent, are

commonly less heavy than in summer, and seldom occur except in association with orographical rain. In the period available for consideration an almost equally great preponderance of orographical rains occurred in March and April, but this may not be normal. During the remaining six months, May to October inclusive, orographical influence was apparent in 67 out of the 72 months, but in 33 cases it was not well marked, leaving 34 months, or 50 per cent., with well-marked influence, and it may be remarked that even these were seldom so definitely characteristic as was the case in the winter. July, in 10 out of the 12 years, exhibited a weak relationship between the rainfall distribution and the configuration. This is the month of greatest frequency of convectional rains, and purely cyclonic rains are also frequent, whilst orographical rains are at a minimum. In the whole twelve years there were only 7 months, or 5 per cent. of the total number, which exhibited a rainfall distribution wholly devoid of orographical influence. Of these, two occurred in June and one each in March, April, May, September, and October. The period is not long enough to indicate the normal seasonal distribution, but sufficient to make it clear that the winter rainfall is most strongly influenced by the configuration of the land, its distribution even over so short a period as one month being practically entirely determined by it ; but during the summer half-year, whilst orographical influence is nearly always apparent, in a large number of cases it is not overwhelmingly strong, and in a small percentage of months it is entirely wanting.

An example of prominent orographical distribution during a winter month is given in Fig. 116.

This month, February 1914, was one of persistent south-westerly winds with frequent depressions

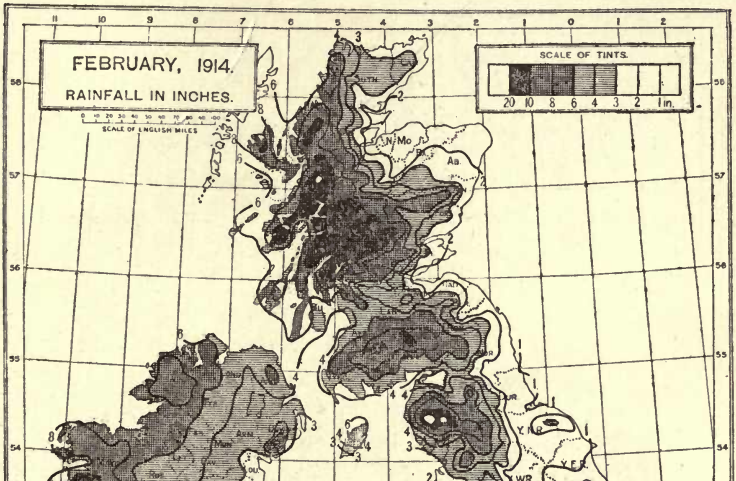


FIG. 116.—MONTHLY RAINFALL DISTRIBUTION—OROGRAPHICAL TYPE.

travelling on unusually northerly tracks. The excess of rainfall on the high land in the west, and in a less degree in the south, is well brought out, as is

also the marked decrease in the fall towards the east coast and in the sheltered estuaries in the west.

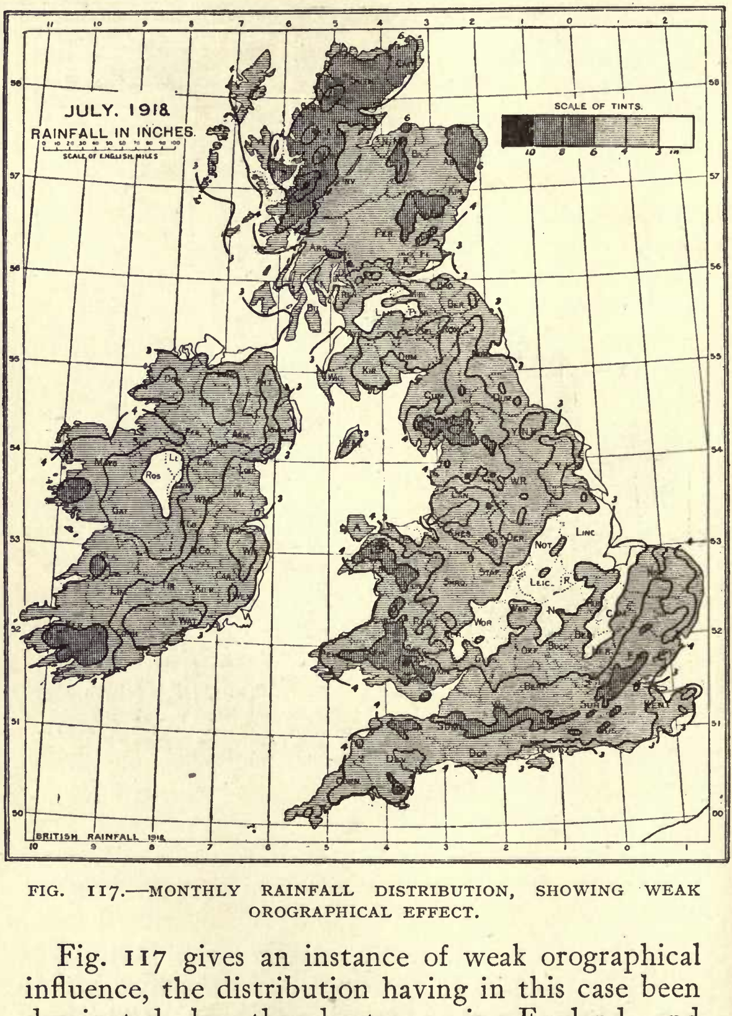


FIG. 117.—MONTHLY RAINFALL DISTRIBUTION, SHOWING WEAK OROGRAPHICAL EFFECT.

Fig. 117 gives an instance of weak orographical influence, the distribution having in this case been dominated by thunderstorms in England and

cyclonic rains in the east of Scotland. In the hilly regions of the west, especially in the north-west

FIG. 118.—MONTHLY RAINFALL DISTRIBUTION WHOLLY DEVOID OF OROGRAPHICAL EFFECT.

Highlands, there is, however, a distinct tendency for the isohyetal lines to fall into the positions typical of

orographical rain, so that the month's distribution as a whole is of an intermediate type.

Among the few cases in which orographical influence is so weak as to be completely overwhelmed by rain of other types, no better example is likely to be found than that which occurred in June 1903. Mention has already been made of the great cyclonic rains in the Thames Valley during this month (see pp. 160–161, *ante*). In the south of the British Isles these rains formed so large a proportion of the whole fall of the month in question that they completely dominate the map, and any orographical rain which may have occurred, at any rate south of lat. 54° N., is not in the least apparent in the run of the isohyets.

A partial inversion of the normal orographical distribution sometimes occurs, especially in the spring months, when, on account of abnormal pressure-conditions, easterly or north-easterly winds persist for any long period. Such winds may be derived from the southern flanks of an anticyclone lying to the north, in which case they usually bring dry, cold weather. In some circumstances, however, easterly winds are associated with considerable rainfall in the east of Great Britain and deficiency in the west. It appears probable that such rains may be attributed to convergence of the easterly drifts on the north side of southerly low-pressure areas with those of the anticyclone. If the duration of any protracted spell of such conditions happens to concide more or less with the calendar month, a distribution like that shown in Fig. 119 results. In Fig. 119 the isopleths indicate the percentage relation of the rainfall in various parts of the country to the average of 35 years, and bring

out the pronounced concentration of the rainfall in the east as compared with the west. Although

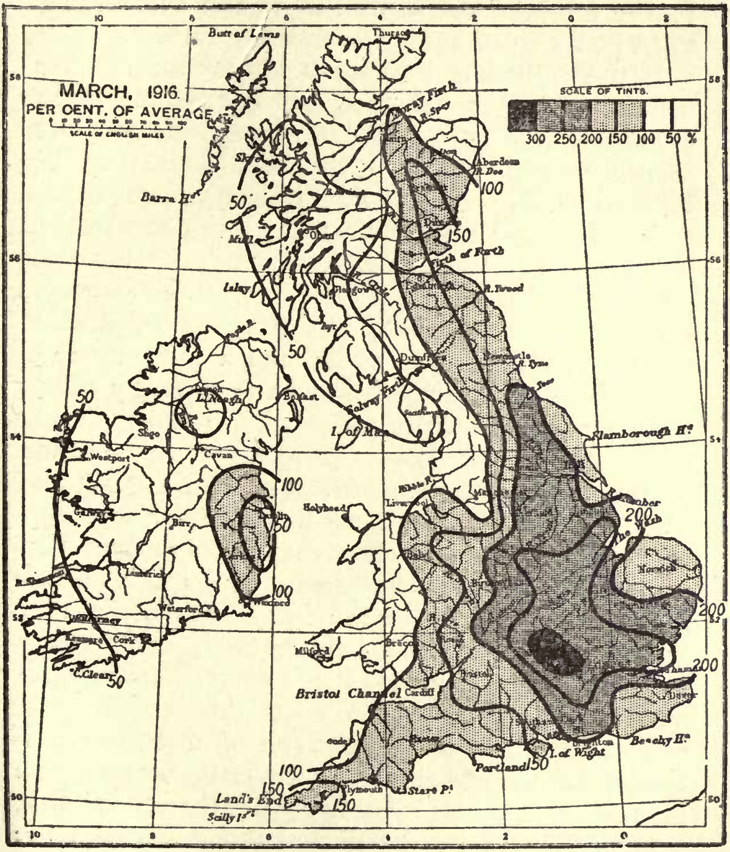


FIG. 119.—MONTHLY RAINFALL IN RELATION TO THE AVERAGE. THE EASTERLY TYPE.

the type of distribution is entirely different in this case from the common orographical type associated

with normal south-west winds, and shows no strongly marked relation to the configuration, it is probable that, physically speaking, the rain is allied to the orographical as well as to the cyclonic and must be regarded as an intermediate variety.

If the period considered is longer, say one year instead of one month, orographical rainfall of the south-westerly type invariably preponderates over all other types. From the records brought together by the British Rainfall Organization, a consecutive series of annual rainfall maps has been constructed going back to 1865, the majority of which have not yet been published. On examining these maps one finds a strong resemblance in the type of distribution throughout the whole series, and a marked correlation between the rainfall and the elevation of the land, giving abundant proof of the truth of the above statement. Figs. 120 and 121, representing respectively the distribution of rainfall in 1903 and 1887, nearly, if not quite, the wettest and driest years of the whole period, show that even in the most extreme variations in the amount of the total rainfall in the year the run of the isohyets does not vary greatly, a line of one denomination in one map merely taking the place of one of another denomination in the other. Whilst this tendency is indisputable so far as the type of distribution is concerned, the appearance of similarity between one map and another is probably greater than the reality, being enhanced by the disproportion between the rainfall totals in the rainy regions and those in the districts of smaller fall. It must not, therefore, be supposed that one year's rainfall observations in any sense fix the true normal distribution. An individual year's rainfall may at any place fall as much as 40 per

cent. below or rise as much as 50 per cent. above the average, and the amount of abnormality varies

FIG. 120.—DISTRIBUTION OF ANNUAL RAINFALL. WET YEAR.

largely from one part of the country to another every year. Thus the maps of the relation of each year's

rainfall to the average, published yearly in *British Rainfall*, since 1905, show that it is not at all in-

FIG. 121.—DISTRIBUTION OF ANNUAL RAINFALL. DRY YEAR.

frequent for an excess of 20 per cent. in the year's rainfall in one part of the country to occur in the

same year with a deficiency of 20 per cent. in another part, and a range of over 30 per cent. of the average from place to place in the same year may be expected every year, though not, of course, at adjacent stations.

Fig. 122 gives an example of the distribution of a year's rainfall in relation to the average of 35 years. On account of the relatively small number of stations for which records over so long a period as 35 years are available, it is possible that the map cannot be accepted as so minutely accurate as an ordinary isohyetal map, where every record can be utilized, but there is no doubt that isopleths indicating percentage variation from an average, if they refer to any period as long as, or longer than, a month, are almost certainly to be expected to be much smoother than isohyetal lines, and it is probable that the addition of a great many more values in plotting the map would introduce very little change in the run of the lines. The year chosen as an example was on the whole wet, though small areas in England and a fringe of the north and west coasts of Scotland had less than their average rainfall. In the tinted area each line indicates a successive departure of 10 per cent. from the average, and the tint is made darker as the fall is shown to be greater relatively to the average. If the year had been one of abnormal preponderance of orographical rains, it is clear that these areas of excess would have been found in the mountain districts, and the fact that this is not the case may be taken to indicate that orographical rains were less prominent than usual in this particular year, and that non-orographical rains of more than ordinary magnitude or frequency occurred in three large areas respectively

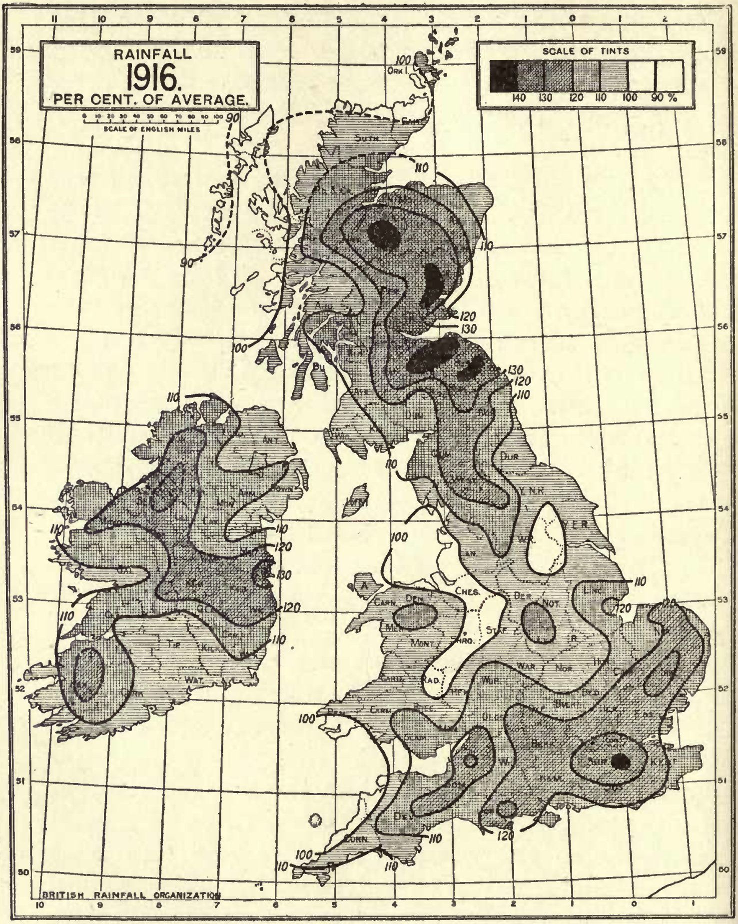


FIG. 122.—EXAMPLE OF RELATION OF ANNUAL RAINFALL TO THE AVERAGE.

in the centre of Ireland, the east of Scotland, and the south-east of England. The fact that the relatively wet areas indicated are large and homogeneous suggests that the non-orographical rains in question

were cyclonic rather than convectional, since the latter, as has been shown, give rise to falls of a very local nature. An examination of the daily and monthly rainfall maps for the year 1916 bears out the correctness of this inference.[1]

It is thus clear that whilst orographical rainfall always preponderates over other types in the course of a year, the extent to which it preponderates is variable. The range of this variability diminishes if, instead of studying the rainfall of a single year, we consider the average during a number of years, and the average of 30 to 40 years[2] probably gives nearly a constant for amount, and consequently for distribution also.

Since 1900 a very large number of maps of the average rainfall for 35 years in various parts of the British Isles have been constructed. Some of these have been published in the Water-Supply Memoirs of the Geological Survey,[3] and a few in other publications, but the majority were constructed for the purpose of private Bills for water-supply or water-power schemes, and are still unpublished.

It is not possible in a book of this size to reproduce any large-scale maps of this nature, but a fragment of the detail is given as an illustration (Fig. 125, p. 277) in Chapter XV, and a greatly reduced copy of the isohyetal lines for the whole country

[1] See *British Rainfall*, 1916.

[2] See A. R. Binnie, *Proc. Inst. C. E.*, vol. cix, pt. iii, p. 89. H. R. Mill, *Proc. Inst. C. E.*, vol. clv, pt. i; *British Rainfall*, 1910, p. [143]. See also *ante*, p. 222–225.

[3] Geological Survey of England and Wales. Water-supply Memoirs for Bedfordshire, Essex, Hampshire, Kent, Lincolnshire, Northamptonshire, Nottinghamshire, Oxfordshire, Suffolk, Surrey, Sussex, Yorkshire (East Riding), published under the authority of the Board of Education.

FIG. 123.—DISTRIBUTION OF AVERAGE ANNUAL RAINFALL.

partly generalized is shown in Fig. 123. In spite of its small scale, this map will repay close study in conjunction with a physical map.

The large-scale average maps and the data upon

which they were based form a veritable mine of information on the subject of the relation of average annual rainfall to the configuration of the land, and it is instructive to state a few of the generalizations which appear to be justified by their study. The field covered is so wide that it is, however, manifestly impossible to give more than a few selected examples, which must be taken rather as illustrative of the underlying principles than in anyway comprehensive.

In all that follows the expression "prevailing wind" must be taken to mean a wind from some quarter between south and west. The words "windward" and "leeward" must be construed in the same sense. The records quoted are in every case the average annual rainfall at the station in question for a period of 30, 35, or 40 years, in the great majority of cases 35 years, and they may, as a rule, be taken as representing the average of a very much longer period within about 3 per cent. In cases where no complete record of the required duration was available, the average of a shorter period has been corrected by means of one or more adjacent long records, so that all figures quoted may be regarded as comparable.[1]

RAINFALL AT OR NEAR SEA-LEVEL

No satisfactory rainfall records exist of the average amount of rain which falls annually over the sea itself in the neighbourhood of the British Isles. If we could obtain trustworthy information on this point we should presumably have a measure of the amount of non-orographical rainfall which falls over the land

[1] Reference to large-scale contoured maps is necessary in order to follow the discussion in detail.

generally, since, except possibly quite close to the shore, no orographical rainfall could occur over the sea.

There are, however, numerous rainfall records at stations at or near sea-level, and it is instructive to examine the variations of average rainfall under these conditions.

On the east coast of Great Britain the smallest average annual rainfall invariably occurs on the shores of the sheltered estuaries.

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Gravesend . . .	Kent	24	20·4
Shoeburyness . . .	Essex	13	19·3
Boston	Lincoln	11	23·4
Fearn	Inverness	95	23·2

There is a small but perfectly distinct increase in the rainfall at similar elevations at less sheltered stations on the coast.

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Walmer . . .	Kent	20	25·9
Southwold . . .	Suffolk	44	24·1
Hornsea . . .	Yorks, E.R.	30	26·8
Wick	Caithness	81	29·9

The only other conspicuous variation near sea-level on the east coast appears to be a general increase from south to north for stations with similar exposures. This fact is possibly connected with the decrease of temperature in higher latitudes, but it may also be associated with the greater frequency of

the passage of cyclonic depressions in the north of the British Isles than in the south.

On the east coast of Ireland the sea-level rainfall values are higher than on the east coast of Great Britain.

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Courtown	Wexford	60	35·0
Dublin	Dublin	54	27·7
Greenore . . .	Louth	20	32·3
Donaghadee . . .	Down	40	31·7

On the south coast of England the average annual rainfall at sea-level exhibits a decided increase from east to west.

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Dymchurch . . .	Kent	12	25·4
Bognor	Sussex	15	26·0
Ventnor . . .	Hants, I. of W.	81	29·2
Wareham . . .	Dorset	18	31·4
Devonport . . .	Devon	20	36·7

There are, however, conspicuous exceptions to this otherwise nearly uniform increase, relatively smaller falls being observed at sheltered stations—

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Emsworth (Thorney) .	Hants	23	26·7
Exmouth	Devon	51	27·7

and relatively larger falls at one or two exceptionally

placed stations. In the case of the two quoted the larger fall is undoubtedly connected with the proximity of high land.

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Hythe	Kent	12	28·0
Eastbourne . . .	Sussex	12	30·9

The west coast of Great Britain differs in some essential respects from the east and south coasts. The most notable differences from the point of view of sea-level rainfall are the much more indented coast-line, especially in Scotland, where sea-lochs extend inland in many places to distances of 20 or 30 miles, and, over a considerable portion of the coast, the existence of high mountains within a few miles of the sea, especially in the north. The sea-level rainfall is everywhere higher than in the south and east, and exhibits a striking, though not uniform, increase from the south to north.

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Scilly	Cornwall	40	32·7
Barnstaple . . .	Devon	25	37·1
Castle Malgwyn . .	Pembroke	30	43·7
Aberdovey . . .	Cardigan	22	37·8
Holyhead . . .	Anglesey	48	35·0
Southport . . .	Lancs.	38	32·7
Barrow . . .	,,	36	38·1
Whitehaven . . .	Cumberland	21	41·7
Auchencairn . . .	Kirkcudbright	50	46·8
Eallabus (Islay) . .	Argyll	68	48·8
Quinish (Mull) . .	,,	35	56·6
Arisaig . . .	Inverness	30	61·8
Scalpay Island . .	,,	4	74·4
Bendamph . . .	Ross	25	86·5

The sea-level rainfall on the west coast of Ireland is higher for the same latitude than that in Great Britain, and shows, on the whole, the same tendency to increase from south to north.

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Darrynane . . .	Kerry	13	49·9
Valentia Island . .	,,	12	56·0
Ennistymon . . .	Clare	37	46·5
Killybegs . . .	Donegal	65	60·6

The rainfall near sea-level at places situated on the shores of sheltered estuaries and sea-lochs on the west coasts shows wide variations from that at more exposed coast-stations. The reasons for these variations involve a consideration of circumstances which will be more conveniently dealt with later.

Except in the case of certain peculiarly situated spots, the average annual rainfall at inland stations at or near sea-level does not differ appreciably from that on the nearest coast; the tendency being on the whole for it to be slightly lower.

The most conspicuous low-lying plain in the British Isles is the Fen district, over the whole of which the average annual rainfall is less than 25 inches, falling to 22·1 inches at Cambridge (35 feet) and 23·0 inches at March (10 feet).

A consideration of the facts enumerated above appears to justify the conclusion that even at elevations only a few feet above sea-level considerable orographical influence affects the amount of rainfall. This is shown by the pronouncedly larger falls on the west coasts, and slightly larger falls on the south coasts than on the east, an effect which seems only

possible on the hypothesis that the rain-bearing westerly and south-westerly winds begin to deposit their moisture freely immediately on coming into contact with the land. It is not impossible that some allowance must be made for the frictional effect of the land surface in impeding the free movement of wind. It is well known that wind-velocities are normally higher over the sea than the land owing to this cause, and the general result of such interference has been pictured as the formation of a sort of cushion of relatively slow-moving air over the land above which the wind moving from the sea would tend to mount, giving rise to ascending currents and consequent rainfall.

After passing across the British Isles the available moisture must be diminished in an important degree, accounting for the relatively small rainfall on the east coast. Such orographical rain as is derived from the North Sea and carried by easterly or north-easterly winds is certainly very much smaller in quantity than that from the south-west quarter, but it is probably to this effect that the relatively high rainfall on the elevated land in eastern Aberdeenshire, the North and East Ridings of Yorkshire, and Norfolk is due. The diminished fall on the shores of estuaries on the east and to some extent on the south coast is obviously due to shelter from rain-bearing winds. It will be observed that the fall is smallest when the shelter is on the south or west side. A similar diminution is to be noted in sheltered estuaries on the west coast:

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Minehead . . .	Somerset	50	31·0
Burnham . . .	,,	18	30·3

In these cases the shelter is distinctly on the south-west. The following are exposed to the south and west and sheltered on the north and east :

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Morecambe . . .	Lancs.	24	40·0
Westport . . .	Mayo	35	46·2

THE INCREASE OF RAINFALL ON WINDWARD SLOPES

Except in a few special cases the average rainfall increases with increased altitude, but the rate of increase per 100 feet varies within wide limits. It is of interest to study the conditions under which such variations occur.

We may first take the simple case of rising land facing the sea, with a gradient approximately parallel to the track of the prevailing wind. Such conditions occur along the slopes of the South Downs in Sussex and part of the eastern extremity of the North Downs in Kent :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Bognor . . .	Sussex	15	26·0	—
Eartham . .	,,	230	29·5	1·6
Selhurst . .	,,	300	32·2	2·2
Bepton . . .	,,	554	37·0	2·0
Brighton . .	Sussex	32	28·7	—
Patcham . .	,,	207	31·8	1·8
Pyecombe . .	,,	392	35·6	1·9
Hythe . . .	Kent	12	28·0	—
Paddlesworth . .	,,	612	38·2	1·7

The above seem to suggest a fairly uniform increase of from 1·5 to 2·0 inches per 100 feet, but the rate may be reduced to a smaller figure if the hill is less continuous, for example :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Birling Gap . .	Sussex	40	26·9	—
Willingdon . .	,,	599	31·4	0·8
Portslade . .	Sussex	167	29·0	—
Poynings . .	,,	580	34·3	1·0

The smaller rate of increase in these cases may be attributed to the facility with which the wind may find its way round an isolated hill rather than being forced to ascend over the summit. A still more remarkable instance will be mentioned later. For exactly the same reason it is usual to find the rainfall lower, for the same elevation, on the slopes parallel to the prevailing wind at the points where the South Downs are intersected by gaps than on the continuous hillsides at right angles to the prevailing winds, that is to say, each isohyet rises to a higher elevation in the gaps than on the exposed slopes.

Comparison may be made with similar data for the inland ridges of the south-eastern countries :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Cranleigh . .	Surrey	175	29·2	—
Malquoits . .	,,	400	31·4	1·0
Ewhurst . .	,,	600	32·2	0·7

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Edenbridge . .	Kent	161	25·9	—
Ide Hill . .	,,	700	30·7	0·9
Botley Hill . .	,,	870	33·5	1·1
Maidstone . .	Kent	30	24·2	—
Detling . . .	,,	336	27·8	1·2
Harrietsham . .	,,	620	31·5	1·2

It will be observed that the rate of increase is smaller than that on the South Downs, an effect probably due to the diminished humidity of the air, and the more pronounced the shelter afforded by the more southerly ridges the smaller does the increase per 100 feet become. An example is given by the slight rate of increase on the southern side of the Forest Ridges in north Sussex :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Buxted Park . .	Sussex	94	30·7	—
Maresfield . .	,,	247	31·2	0·3
Nutley . . .	,,	386	31·6	0·3
Crowborough . .	,,	777	35·1	0·6
Warbleton . .	Sussex	182	31·4	—
Tottingworth .	,,	500	32·4	0·3

The falling-off of total rainfall at the same altitude with increasing distance from the sea, coupled with the shelter of the intervening hills, is illustrated by the following. The distance from the sea is measured approximately in a south-westerly direction :

Station.	County.	Distance from sea.	Altitude.	Average annual rainfall.
		miles.	ft.	in.
Bepton . . .	Sussex	15	554	37·0
Worth . . .	,,	25	558	34·4
Chipstead . .	Surrey	40	550	30·5
Ash . . .	Kent	50	540	27·0

The rates of increase above cited do not cover the whole range of variation, and one interesting anomaly may be mentioned. In the case of fairly steep ridges close to the sea it is commonly found that the maximum rainfall occurs slightly on the leeward side of the crest, irrespective of the altitude of the spot on which it falls. This phenomenon often gives to an individual station, which happens to be so situated, a rainfall greatly in excess of that otherwise proper to its altitude. An example may be seen in the South Downs at Lavington, immediately to the north of the highest part of the Downs, which rise to over 800 feet, but itself at an altitude of only about 250 feet. The average rainfall is 40·1 inches, probably the largest observed in any part of the south-east of England. Similarly at Alciston, near Polegate, Sussex, 33·9 inches falls at an altitude of only 172 feet, whereas at Willingdon, only 6 miles distant and situated 599 feet above the sea, only 31·4 inches falls.

It is clear from a general survey of the distribution of rainfall in the south-east of England, that the average fall is wholly governed, in the first place by the capacity of the land in the district to produce an uplifting effect on the prevailing winds, and, secondly, by the amount of condensable moisture remaining available in these winds after passing over the land between the station and the sea.

The conditions which obtain in the south-east of England hold good in the west also, but in this case we have to deal with not only a very much larger sea-level rainfall, but very much more elevated and continuous hill-slopes. A fairly good example may be found in central Wales :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Aberystwyth . .	Cardigan	15	35·6	—
Goginan . .	,,	290	46·2	3·9
Cwmsymlog . .	,,	800	55·5	2·5
Waenbwll . .	,,	1,380	67·4	2·3
Plynlimon . .	,,	1,740	94·0	3·4
Aberaeron . .	Cardigan	50	35·6	—
Abermeurig . .	,,	300	46·0	4·2
Tregaron . .	,,	520	50·0	3·1
Maes-y-bettws .	,,	910	66·6	3·6
Towy-fechan . .	,,	1,330	72·1	2·8
Cors-yr-hwch . .	Radnor	1,775	87·5	3·0

There is a fairly close agreement in the rate of increase in these cases, which, it will be noted, is about double that observed on the South Downs. With the steeper gradients of the Snowdon range the rate of increase is still further augmented :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Glynllivon . .	Carnarvon	100	44·1	—
Nantlle . . .	,,	450	61·2	4·9
Llanllyfni . .	,,	751	73·9	4·6
Cwmsilian Lake .	,,	1,100	81·0	3·7
Moel Hebog . .	,,	1,500	112·2	4·9
Lluchfa . .	,,	2,500	161·0	4·9

The last-named station is one of a group situated

in the vicinity of Llyn Llydau on the immediate east of the great escarpment of Snowdon, and presents an undoubted example of the phenomenon already referred to, viz. the occurrence of the maximum rainfall immediately on the lee side of the highest land. If we regard the rainfall at Lluchfa, which is fairly representative of Cwm Llydau, as the result of the obstruction to the prevailing wind caused by a ridge of 3,500 feet altitude, the rate per 100 feet works out at 3·4 inches.

The English Lake District presents a parallel instance to the Snowdon group, but the seaward slopes of the Lake District mountains are singularly devoid of rainfall stations at representative altitudes, the great majority being situated in the deep-cut valleys which radiate from the centre towards the sea. We may, however, quote :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Ravenglass . .	Cumberland	80	42·3	—
Sca Fell Pike . .	,,	3,200	137·8	3·1
Sprinkling Tarn .	,,	1,985	128·1	4·5
The Stye . .	,,	1,070	176·9	13·6

The last-mentioned is another famous example of the shifting of the maximum rainfall to the leeward, and if we regard the mass of the Great Gable, rising to 2,900 feet, as the controlling factor, we get an increase of 4·8 inches per 100 feet from sea-level, showing a fair agreement instead of the very large and certainly deceptive value of 13·6 inches shown by calculating from the station elevation.

The rate of increase of rainfall per 100 feet on the windward slopes of the Helvellyn and High Street ridges, which lie in the direct shelter of the central Lake District mountains, is in very striking contrast to the high values quoted above :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Dale Head Hall .	Cumberland	620	78·5	—
Whiteside . .	,,	2,100	85·0	0·4
Grasmere . .	Westmorland	553	83·3	—
Fairfield . .	,,	2,860	95·5	0·4
Ambleside . .	Westmorland	180	76·2	—
Kirkstone . .	,,	1,500	98·3	1·7
Grey Crag . .	,,	1,750	98·0	1·4

Too much weight must not be given to the exceptional values at Whiteside and Fairfield, on account of the uncertainty which always attaches to rain records on high and exposed moorlands.

Except where westerly winds find free access the rate of increase on the western slopes of the Pennines is small. At the point selected as an example the Pennines are sheltered by the Snowdon range, and the conditions may be taken as representative of the less exposed parts of the ridge :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Chelford . .	Cheshire	250	29·7	—
Macclesfield . .	,,	501	34·0	1·7
Leek . . .	Stafford	750	38·2	1·7
Axe Edge . .	Derby	1,600	55·8	1·9

The changes in the rate of increase of rainfall per 100 feet under varying conditions of shelter, gradient, and distance from the sea are well brought out in the cross-section through the Lake District and Pennines in Fig. 124. It is significant to note the ready response of the rainfall curve to the changes in the altitude curve in the west, and the diminishing effect of high land to the leeward of the most westerly hill-barriers. This diminution in the amplitude of the rainfall curve is particularly noticeable on the Pennines, where the slopes of Marton Fell and Cross Fell, directly facing the prevailing wind, experience a rainfall very much inferior to that of the Lake District.

In order to illustrate the absolute dependence of the average rainfall upon the capacity of the land to exercise an uplifting effect upon the prevailing wind, it is of interest to refer to a single example of low rate of increase which may be explained upon physical grounds. The hill in question, Pendle Hill, rises to a height of 1,800 feet, and enjoys an almost uninterrupted exposure to the rain-bearing winds blowing up the Ribble Valley. Records on the south-western slopes give the following values :

Station.	County.	Altitude.	Average annual rainfall.	Increase per 100 ft. from base station.
		ft.	in.	in.
Gawthorpe . .	Lancashire	316	41·4	—
Sabden . . .	,,	500	43·3	1·0
Ogden Reservoir .	,,	935	46·2	0·8

The shape of Pendle Hill, which is an isolated mass, may be compared to that of an overturned boat, with the bows pointing to the south-west. On this

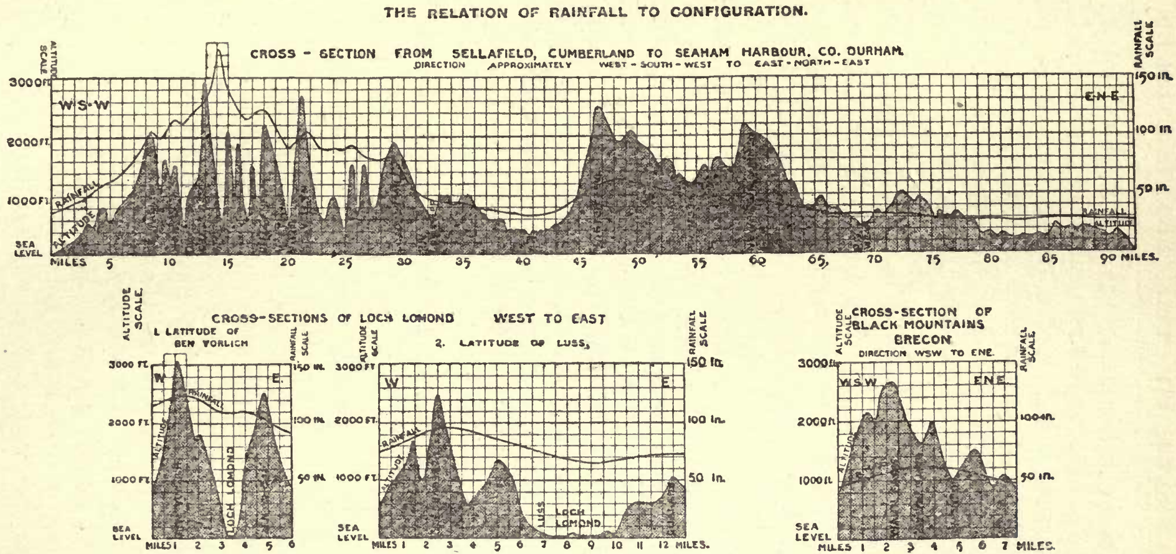


FIG. 124.—CROSS-SECTIONS SHOWING RELATION OF AVERAGE ANNUAL RAINFALL TO THE CONFIGURATION OF THE LAND.

account the wind coming up the Ribble Valley is able without hindrance to find its way past the rising land without being forced to ascend over the summit, except possibly to a limited extent. The case of Pendle Hill is no doubt exceptional, but it is certain that, generally speaking, the rate of increase of rainfall per 100 feet on hillsides parallel to the prevailing wind is lower than it is in the case of slopes directly facing the wind. This tendency is greater according as the hill is more isolated. This fact has already been mentioned in dealing with the rainfall of the South Downs, but the disparity which it brings about is very much larger in the west. An interesting corollary in the case of Pendle Hill is the fact that the rainfall of the valleys lying immediately to the north-west, north-east, and south-east of the ridge appear to have an average rainfall rather higher than might normally be expected, no doubt owing to the convergence of wind-currents deflected from its slopes.

Decrease of Rainfall on Leeward Slopes

On the leeward slopes of high land, save in the exceptional cases already referred to, the amount of rainfall diminishes steadily as the prevailing winds gradually descend to lower levels. If these winds have passed over land with an extremely high rainfall, they will be largely drained of their available moisture; whereas if they have parted with only a moderate proportion of their water-content, the residue available for precipitation on the leeward slopes will be the greater. It should be noted that descending air is being steadily warmed by the increasing pressure above, so that its capacity for

retaining moisture is increasing. The tendency for rain to condense is therefore proportionally less than was the case at equal levels on the windward slopes.

In the case of the Pennines it is convenient to state the rate of decrease of rainfall per 100 feet in general terms rather than by quoting individual records. From a number of measurements the rate of falling-off in annual rainfall is found to be, broadly speaking, 1 inch per 100 feet above 1,000 feet, increasing to 2 inches per 100 feet below 500 feet of altitude, measuring in each case from the summit of the ridge. The rate is higher in the districts where the Pennine range is exposed on its western side to the full effect of the south-west wind. It will be observed that in the case of the Pennines the rate of decrease is more rapid at low levels, on the extreme east, than at high levels. This, no doubt, arises from the cumulative effect of continued desiccation of the air.

On the eastern slopes of the Snowdon group of mountains the decrease per 100 feet is larger and more irregular than on the Pennines. The irregularity shown is possibly due to the difficulty of selecting representative stations uninfluenced by local conditions.

Station.	County.	Altitude.	Average annual rainfall.	Decrease per 100 ft. from highest station.
		ft.	in.	in.
Upper Eigiau	Carnarvon	2,000	121·5	—
Caedryn	,,	1,250	107·2	1·9
Lake Cowlyd	,,	1,168	86·2	4·2
Lower Brwynog	,,	1,000	66·8	5·5
Dolgarrog	,,	22	50·2	3·6
Llyn Dulyn	Carnarvon	1,632	103·6	—
Eigiau Dam	,,	1,245	84·9	4·8
Frith Rhos	,,	1,100	71·3	6·1
Llanbedr	,,	510	56·2	4·2
Tal-y-cafn	,,	75	44·2	3·8

Similar high rates obtain to the east of the Plynlimon range:

Station.	County.	Altitude.	Average annual rainfall.	Decrease per 100 ft. from highest station.
		ft.	in.	in.
Plynlimon . .	Cardigan	1,740	94·0	—
Dylive . . .	„	1,300	71·0	5·2
Carno . . .	„	595	49·9	3·8
Plynlimon . .	Cardigan	1,740	94·0	—
Pantmawr . .	Montgomery	1,080	65·1	4·4
Dernol . . .	„	850	56·1	4·3

The rainfall at the base of a mountain range is commonly lower on the leeward side than on the windward, and the diminution is intensified in the case of land to the leeward of exceptionally wet districts, giving rise to the phenomenon sometimes known as "rain shadow." A good example is seen in the lower Spean Valley, immediately to the north-east of Ben Nevis, where an average of only 53·7 inches falls annually at Roy Bridge (307 feet). In the unsheltered Lochy Valley a few miles west, at a lower altitude, about 70 inches falls. In the Eden Valley, sheltered by the mountains of the Lake District, the average rainfall is as low as 34·4 inches at Appleby (440 feet) and 32·2 inches at Carlisle (115 feet), compared with about 50 inches at the same altitudes on the south-west of the Lakes (see Fig. 124). A similar effect is seen in Glengarry, near Blair Atholl, Perthshire (420 feet); in the Clwyd Valley in North Wales; and on a larger scale in the low rainfall of the Vale of York, and of the central basin of the Shannon.

Rainfall in Narrow Valleys

Many instances are to be found, particularly in the West Highlands, of stations at low elevations, in some cases nearly at sea-level, with rainfall values very much higher than would seem to be appropriate to their altitudes. We may mention, for example:

Station.	County.	Altitude.	Average annual rainfall.
		ft.	in.
Arrochar . . .	Dumbarton	50	91·8
Ardlui . . .	,,	50	113·2
Glencoe . . .	Argyll	20	84·7
Fort William . .	Inverness	33	75·9
Glenfinnan . .	,,	50	108·8
Bendamph . .	Ross	25	86·5

An examination of a large-scale contour map shows that these stations are situated, without any exception, in the bottoms of steep-sided valleys of no great width, between lofty hills, obviously carrying a high rainfall. The conclusion is justified that narrow valleys, and, we may add, particularly those transverse to the direction of the prevailing wind, partake of the rainfall of the surrounding hills. This fact alone renders it impossible to compute any general formula for the increase of rainfall with elevation, and makes it necessary to study every record in the light of the configuration of the surrounding country. The degree of completeness with which the rainfall on valley floors represents that on the surrounding plateau diminishes with valleys of greater width. A case in point may be seen in the neighbourhood of Loch Lomond (see Fig. 124), where a number of stations, about 50 feet above sea-level, on the west bank of the loch, give

values of about 110 inches under the shadow of Ben Vorlich, and 90 inches under Ben Bhreac, where the loch is about half a mile wide. At Luss, 70 feet, or about the same elevation, but where the loch is 3 miles wide, only 77 inches falls, and at Balloch (91 feet), at the south end of the loch, only 50 inches. The instance may also be mentioned of Fort William, situated practically at sea-level, at the head of Loch Linnhe, and immediately at the foot of Ben Nevis, which rises to 4,407 feet on the east-south-east. The average annual fall at Fort William is 75·9 inches, and that on the summit of Ben Nevis 162·6 inches, giving an increase of 2·0 inches per 100 feet. Taking into consideration the very steep gradient of the mountain between Fort William and the summit, and also the westerly position of the stations, the rate of increase is a low one, indicating that the fall at Fort William, though only about half that of the higher station, is larger than the fall proper to its altitude at that latitude.

Transverse valleys are undoubtedly more apt to participate in the high rainfall of the surrounding hills than are valleys parallel to the prevailing wind, though the latter do so to some extent, particularly if very narrow. The probability of the phenomenon occurring diminishes with distance from the west coast, and it is rather a striking feature of the narrow valleys of the eastern slope of the Pennines that they carry a low rainfall far up among the hills.

Instances are occasionally met with in which the phenomenon of sustained high rainfall over valleys transverse to the prevailing wind with that of the shifting of the maximum fall to the leeward of the highest land, previously referred to, combine to

give a rainfall actually higher over the valleys than over the hills; this is the case in some of the deep-cut valleys of South Wales, notably in the Black Mountains of Breconshire (see Fig. 124).

A point of some importance with regard to the distribution of rainfall in the neighbourhood of narrow valleys, particularly near the west coast, is that a considerable modification in the direction of the surface winds is sometimes brought about by the trend of the valley. Thus, for example, a wind entering the mouth of a valley from a south-westerly direction may pass along lateral valleys as a south-east wind, retaining, however, all the rain-bearing characteristics of a south-west wind. In these circumstances the increase of rainfall per 100 feet on the hillsides up which the wind is being forced to rise will be higher than would probably be the case in a valley to which only true south-east wind could gain admittance.

It must be repeated that the foregoing statements and examples must be taken only as illustrative of some of the outstanding features of the distribution of rainfall in its relation to configuration. The statements are of necessity somewhat general in character, and the examples frequently somewhat local in application.

It is clear that any quantitative generalisations must only be accepted subject to the reservation that the limits of variation therefrom are of great magnitude. There appears to be no way in which to arrive at any clear conception of the physical processes underlying these variations except by the patient study of rainfall records in conjunction with large-scale contoured maps. For this purpose the 2 miles to 1 inch Ordnance Survey "layer" map

of the British Isles, or its precursor of the same kind produced by Bartholomew long before the Ordnance Survey published this very convenient map, will be found an effective guide to the details of the configuration of the land.

CHAPTER XV

THE ECONOMIC APPLICATION OF RAINFALL DATA

The pursuit of any branch of natural science is primarily of value not because of any specific practical end to which the knowledge gained may be applied, but on account of the part it plays in the development of the human intelligence. It is a natural and laudable instinct which prompts the pursuit of knowledge for its own sake, and the enunciation of a fact, even though marred by our imperfect appreciation of its true meaning, or our inability to apply the information to our ends, is in itself an achievement worthy of the utmost effort. All scientific knowledge can, however, be utilized for economic purposes, because the more fully we understand natural laws the more surely can natural phenomena be made to serve our needs.

The direct importance of information as to the laws governing the phenomenon of rain and as to its incidence and distribution is manifest when it is realized that we are entirely dependent upon rain as the only source of fresh water, of all elements the most indispensable to life. The great abundance of water in the British Isles—an advantage which we owe to our geographical position—renders this country immune from the devastating droughts which are common in some parts of the world, and it is comparatively rare for any serious or widespread

famine to occur merely on account of lack of rain. The British Isles are also greatly favoured in this respect by the fact that, the bulk of the rainfall being orographical, the mountainous districts, which lie principally in the west, enjoy a sufficiently large and continuous rainfall to feed numerous rivers which carry away their superfluous precipitation across the relatively drier plains of the east. The continual renewal of the supply of water in excess of the actual needs of vegetation allows of large accumulations in the permeable underground strata, such as chalk and sandstone, so that even in the event of long periods of rainless weather, supplies can usually be obtained from springs or borings.

All applications of rainfall data to economic purposes involve a consideration of certain points beyond those dealt with hitherto. These may be grouped under three heads : (i) The interpretation of rain gauge readings in terms of volume of precipitation; (ii) the losses to which the precipitated water is subject after reaching the ground; and (iii) the relation of the flow of streams and the fluctuations of underground water to the rainfall.

The computation of the actual volume of rainfall from observations has been placed on a much more secure basis than formerly by the elaboration of the cartographical method of treatment. Strictly speaking, a rain gauge measurement can only be applied with certainty to the actual spot upon which the instrument is placed. If it is necessary to ascertain the volume of rainfall over an area, it is obviously necessary to know the amount of the fall in all parts of that area and the quantity which has fallen in the ungauged portions must be inferred. Considerable experience is required before this

inference can be made without serious risk of error.

In constructing a rainfall map for the purpose of a volumetric determination, it is important to take every precaution that the records plotted are synchronous. The plottings should not be confined strictly to the area under consideration, but should extend to some distance on every side, since much light may be thrown on the distribution of the fall within the area from that in the adjacent districts. The method of drawing the isohyets differs considerably according to the period which is being dealt with and the nature of the country. It is frequently necessary, for example, to ascertain the volume of water precipitated during a single shower in order to relate it to the magnitude of a flood, and in such a case it is of first importance to ascertain whether the rainfall in question was of the thunderstorm type or whether it was more definitely cyclonic or orographical in origin. For this purpose pressure-maps are of great utility, but the type of rainfall can usually be adjudged by extending the area mapped until the characteristics of the distribution declare themselves. The examples of regional distribution given in Chapters X and XI will enable the reader to form an opinion as to the manner in which a skilled draughtsman may employ analogy in interpreting the measurements over any individual area in terms of a rainfall map. If the distribution shows signs of being definitely orographical, the accuracy of the isohyets may be greatly improved by taking advantage of the details of configuration shown on a contoured map. The use which can be made of the orographical features increases if the period dealt with is considerable and

if the district is definitely hilly. In maps of the average rainfall during a long term of years, such as are required for computing the average water-yield of a gathering-ground for water-supply or water-power purposes, it is imperative that every detail of the orography in its relation to the prevailing rain-bearing wind should be taken into account. In the absence of actual observations it is justifiable to direct the run of the isohyets, or to indicate hypothetical dry or wet areas, in the manner which analogy with better represented districts shows to be the most probable. It is important that this principle should be fully recognized in any determination of the probable yield of a catchment area which is to be utilized for the purpose of constructing water-works or installing hydro-electric plant, since any appreciable error in evaluating the volume of water which can be impounded may involve a useless expenditure of many thousands of pounds or the failure to provide for the essential requirements for domestic or industrial purposes of large centres of population.

Fig. 125 gives an example of the method of preparing a preliminary determination of the rainfall of areas for water-supply purposes. The map in question was constructed by Dr. H. R. Mill and the author in connexion with the scheme laid before Parliament in 1913 for providing an additional 58 million gallons of water per day for the city of Glasgow. The problem which it was necessary to solve was to ascertain how much water could be abstracted from the catchment area of Loch Katrine and how much additional supply could be obtained by building a dam across the mouth of Loch Voil in the adjacent valley on the north.

At the date when this scheme was prepared, the number of rainfall records available in the immediate neighbourhood of the lochs in question was not great, and a few of those records which did exist were of doubtful accuracy. It was, therefore, necessary to rely to a considerable extent on analogy and hypothetical reasoning in constructing the map. The period dealt with was the 35 years 1878 to 1912. Only a small number of the records available covered the whole of this period, and these few long records were utilized for the purpose of reducing shorter records to their equivalent for the 35 years. The method by which this is done is to ascertain from the long records the percentage of the 35 years' average which fell in any particular short period, and to apply this percentage as a correction to the average value derived from the short period. For example, the record at Corriearklet, 3 miles south of the head of Loch Katrine, covered only the 8 years 1905 to 1912, the annual average being 91·81 inches. An examination of the long records at adjacent stations showed that during these 8 years 101·8 per cent. of the average for 35 years fell, and reducing 91·81 inches in the ratio 101·8 : 100 we get 90·2 inches. All the short records were weighted in this manner before placing them on the map, for which purpose they were rounded off to the nearest inch. In the case of records which critical examination proved to be in error, the totals for the years in which errors occurred were either rejected or amended by the help of neighbouring records.

In a few cases of gauges placed on exposed mountain slopes a special test was applied. In these circumstances it is reasonable to expect that the catch during the winter months may be defective,

owing to the action of wind. In order to ascertain whether this was so, the recorded fall during the winter half-year was tabulated separately from that during the summer half-year. The same process was followed for several other neighbouring records of known accuracy. If in the case of over-exposed gauges the percentage of catch in the winter was found to be substantially in accord with that at the standard stations, accuracy was assumed; if, on the other hand, it was found to be deficient in comparison with the standard stations, a special correction was applied.

The following table shows the application of this method:

Station.	No. of years.	Annual average.	Percentage of rain in winter, half-year.		Corrected values.	
			Actual (rejected).	Standard (adopted).	Average for period.	Average for 35 years.
		in.			in.	in.
Ben Lomond .	35	88·26	*54*	59	98·20	98·2
Ledard . .	35	59·55	*48*	59	74·80	74·8
Ben Ledi .	6	70·14	*55*	60	79·47	75·9

As an additional precaution against error, the rain gauges in operation at the time of the inquiry were specially inspected and their accuracy tested, care being taken to note any peculiarities of their exposure.

The whole of the actual or computed average values for 35 years were plotted on a copy of the reduced Ordnance Survey map on the scale of 2 miles to 1 inch, on which the configuration is indicated by tints between the contours of altitude, so that the hills and valleys are thrown into relief. Isohyetal lines were then drawn indicating the distribution

of rainfall, based primarily upon the plotted values, but in respect of their direction guided also to a large extent by the configuration, giving effect to the principles laid down in the preceding chapter. Most of the rain gauges in this region lay in the valleys, and in drawing the lines over the intervening mountains the course followed was that which mountain records in other similar districts showed to be the most probable.

Shortly after the construction of this map several additional rain gauges were established at selected spots in and around the Loch Katrine gathering-ground, and when the records for about 18 months were available, they were specially worked up, weighted as described, and added to the map. The computed average values for these gauges are shown on the map within rings. Their indications provided a perfect test of the accuracy of the reasoning upon which the run of the isohyets had been based. Practically without exception they fitted into their places in the scheme of lines, so that no modification was required and the map stood confirmed as originally drawn.

This fact does not of course imply that a rainfall map can always be constructed with certainty from meagre data. The fewer the records available, the greater is the risk that an erroneous measurement may be inadvertently accepted as accurate, and it is highly desirable that on any map the number of points of observation should be large enough to enable an inaccurate record to be detected by its want of harmony with the remainder.

The map being completed, planimeter measurements were made of the areas lying between each successive isohyet, and for each of the zones thus

separated an appropriate general rainfall value was assigned by inspection of the map.

The actual measurements are given in the following summary. Multiplying the area of each zone by its general rainfall gives the volume of rainfall in square-mile-inches, and the total of all the volumes is the volume of rain falling in an average year over the whole area. The number of square-mile-inches can be readily converted into gallons or any other volumetric unit.

CALCULATION OF VOLUME OF RAINFALL

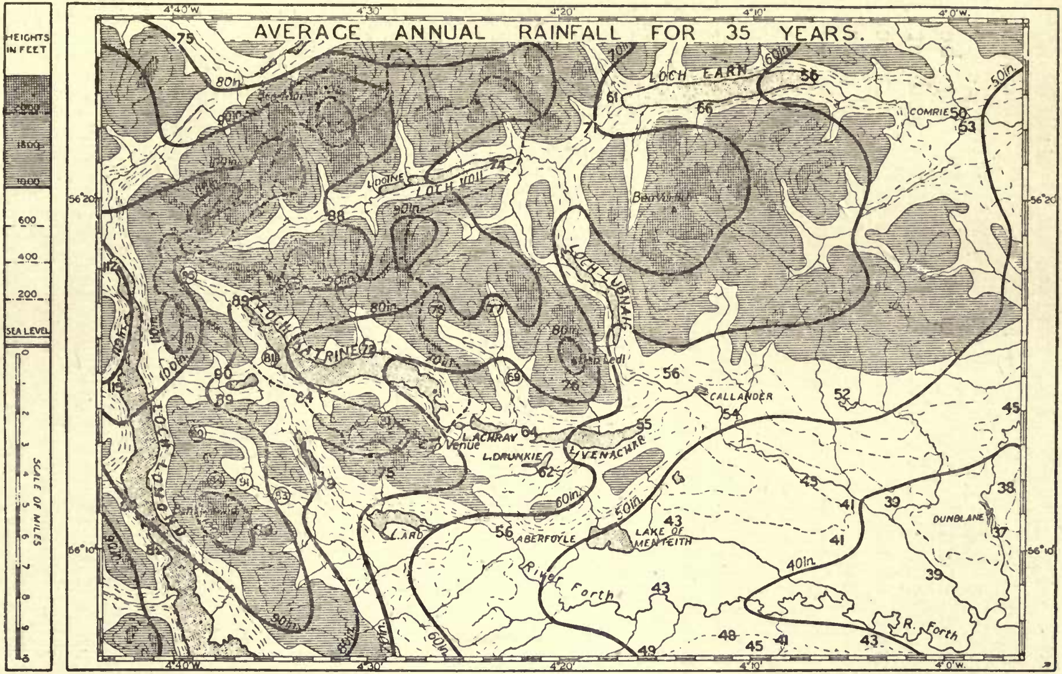
Loch Voil Catchment Area

Zone.	Area.	General rainfall.	Volume of rainfall.
	sq. miles.	inches.	sq.-mile-ins.
Less than 80 inches . .	4·0	77·5	310
80–90 ,, . . .	14·3	86·0	1,230
90–100 ,, . . .	14·5	94·0	1,363
100–110 ,, . . .	5·1	101·8	519
More than 110 ,, . .	0·3	112·0	34
Total	38·2		3,456

Loch Katrine Catchment Area

Zone.	Area.	General rainfall.	Volume of rainfall.
	sq. miles.	inches.	sq.-mile ins.
Less than 70 inches . .	3·8	69·0	262
70–80 ,, . . .	10·0	74·5	745
80–90 ,, . . .	14·3	83·8	1,198
90–100 ,, . . .	5·0	93·8	469
More than 100 ,, . .	3·1	103·0	319
Total	36·2		2,993

If it is desired to ascertain the general rainfall over the areas as a whole, this is arrived at by dividing the total volume by the total area. In the case of Loch Voil this works out at 90 inches, and for Loch



F.G. 125.—MAP SHOWING THE DISTRIBUTION OF AVERAGE ANNUAL RAINFALL IN THE UPPER FORTH VALLEY, CONSTRUCTED FOR THE PURPOSE OF COMPUTING THE WATER-YIELD OF CATCHMENT AREAS.

Katrine 83 inches. The volume of rainfall in an average year for the two areas is 50,041 million gallons and 43,337 million gallons, respectively.

The example which has been given may be regarded as typical of the most accurate method yet devised of utilizing rainfall records for the purpose of computing the volume of water precipitated over any given area in any definite period. It can be applied with the necessary modifications to a large group of engineering problems, including, besides those already enumerated, the design of sewerage and drainage works, the conservation of rivers, and the maintenance of canals.

In all cases where Parliament is applied to for authority to impound any area for the purpose of abstracting water, provision is made for a certain fraction of the natural flow to be returned to the stream as so-called "compensation water," in order that its bed may not be dried up. The determination of the amount of compensation water depends entirely upon the rainfall, and the accurate gauging of rainfall, therefore, becomes a matter of public interest. It is highly desirable that the life of streams should be safeguarded in this way, not only on account of milling and fishing rights, which are commonly looked after by zealous owners, but in the interest of sanitation and of preserving the natural beauty of the landscape. It appears, therefore, to be a public duty for landowners to keep records of rainfall and for an expert public authority to undertake their supervision and interpretation.

It has been shown how, within limits, the volume of rainfall can be ascertained. It is necessary, however, to bear in mind that under natural conditions only part of this volume actually perco-

lates into the ground or flows away in streams. A portion is re-evaporated and lost, and in all volumetric computations some allowance must be made on this account. In dealing with a small area it is sometimes found that in addition to the loss by evaporation, a portion of the water which percolates into the soil will also be lost. This percolated water sinks through the permeable rock and feeds springs, some of which emerge at the outcrop of the lower impermeable strata. Loss occurs on any individual catchment area if the outcrop lies beyond its limits, but the conditions under which such leakage can take place are so variable that it is impossible to generalize as to its amount.

The amount of evaporation can be determined by observation by more than one method, but it is difficult to say how far the results of observations under artificial conditions can be safely applied for practical purposes. The most usual observations are those made by exposing a body of water to the air and measuring the change of level, allowance being made for rain by means of an ordinary rain gauge placed alongside. Many early observations on these lines were seriously in error because the vessel used was too small and consequently became unduly heated by the sun. The standard evaporimeter now used in this country is a tank 6 feet square and 2 feet deep, containing about 450 gallons of water, and sunk in the ground to nearly its full depth.

Continuous observations have been carried on with a tank of this size at Camden Square, London, since 1885, and at several other stations for shorter periods. The results appear to indicate that there is a range of only a few inches between the results at different stations. The amount of evaporation

apparently depends chiefly upon temperature and sunshine.

The average evaporation per year at Camden Square is 15·5 inches, the highest value recorded being 19·5 inches, or 25 per cent. above the average, in 1911, and the lowest 12·6 inches, or 19 per cent. below the average, in 1888, the fluctuations being thus markedly smaller than those of rainfall. There is a strongly accentuated seasonal variation, 87 per cent. of the total occurring during the summer half-year.

A second method of arriving at the amount of evaporation is by means of percolation gauges. The gauge consists of a block of earth, usually 1 cubic yard in volume, enclosed in a water-tight casing open at the top. The water which passes through the gauge is collected and measured, and the difference between this amount and the total rainfall gives an indication of the loss by evaporation. A percolation gauge is only practicable in districts where the rainfall is moderate, since in regions of high fall part of the rain runs off the surface of the ground without percolating. The results will obviously differ with soil of varying permeability, and they are thus not of general application, but the records nevertheless yield valuable supplementary information.

The most complete series of records of this kind are those kept since 1870 at the Rothamsted experimental station of the Lawes Agricultural Trust, near Harpenden.

The Rothamsted soil is described by Dr. N. H. J. Miller as a rather heavy loam, with a reddish-yellow subsoil over chalk, both containing flints.

The average evaporation deduced from the

Rothamsted observations is 15·3 inches per annum, ranging from 19·1 inches, or 25 per cent. excess, to 11·9 inches, or 22 per cent. deficiency, thus showing a very close agreement with the Camden Square records.

The seasonal range of evaporation from soil is, however, somewhat different, as is shown by the following comparison.

—	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
Cam. Sq. tank .	·11	·25	·66	1·53	2·41	2·89	3·01	2·31	1·38	·62	·25	·09	15·51
Rothstd. soil .	·37	·50	·88	1·37	1·59	1·77	2·05	2·11	1·77	1·59	·81	·51	15·32

Neither method of observing reproduces precisely the conditions of nature. In the percolation gauge the water once taken out and measured cannot rise again to the surface, but in natural conditions the roots of plants and especially trees draw large quantities of water from the subsoil and give it to the air by transpiration. This is especially the case when the soil is dry, whereas no evaporation can occur from a dry percolation gauge. The evaporation tank, on the other hand, errs in the opposite direction. In all circumstances it offers an unlimited supply of water for evaporation, whereas when the soil is dry the amount available must be limited. This is undoubtedly the explanation of the difference between the two results for the summer months, and it is reasonable to suppose that the truth lies between the two extremes. The differences in winter are less marked and are probably accounted for by the fact that the percolation gauge, being

covered with grass, offers a larger evaporating surface and is usually in a moist condition at this season.

In applying these results generally it is commonly assumed, with some justification, that the amount of evaporation diminishes from south to north. Over the Pennine district empirical observations of the difference between rainfall and the yield of water-supply catchment areas suggests an annual loss of about 14 inches, and in Scotland the amount probably falls to 10 or 12 inches.

Whilst the average loss by evaporation is fairly well established, the actual loss occurring during long dry periods, a matter of great importance to water-works engineers, is still uncertain, and it is desirable that more extensive observations should be made of this important factor.

The actual rainfall, less an appropriate allowance for loss by evaporation, and if necessary for percolation, has been termed the Effective Rainfall. This represents the best estimate which can be made of the amount of water which actually finds its way into streams and rivers. The actual flow can, of course, be measured by means of weir-gauges. The relation between the flow of water in any individual river and the effective rainfall over its basin is a subject which has long engaged the attention of hydraulic engineers, and many empirical formulæ have been suggested for expressing it. The consideration of these formulæ in detail is beyond the scope of this book, and it is only necessary to make a few general observations.

Assuming that the total flow is, in the long run, equal to the volume of effective rainfall, the extent to which the fluctuations in the fall will be reproduced in the flow of a river varies within wide limits.

It may be taken as an invariable rule that the fluctuations of the run-off will be smaller than those of rainfall. The extent to which the rainfall fluctuations are smoothed out depends primarily upon the size of the catchment area, being greatest in large river valleys and smallest in mountain streams with steep gradients. The flow-off is more rapid in winter than in summer, and is greatly impeded by the presence of vegetation, particularly by forests. It has frequently been stated that denudation of forest areas has resulted in a diminished rainfall, but it appears to be highly probable that this is a fallacy, arising from the fact that in these circumstances run-off is accelerated, causing streams to be more frequently dried up in summer.

An important factor in relation to the flow of streams is the accident of whether the precipitation takes the form of snow. In upland districts, particularly in the north, a large proportion of the winter fall remains on the ground in this form until warm weather returns in the spring or even summer, when it rapidly flows off in heavy floods. This introduces a complication for which it is extremely difficult to allow.

Another complication arises from the occurrence of prolonged frost. The flow from any area is greatly diminished during such conditions, and there is a corresponding excess of flow on their termination. On the other hand, should rain fall upon frozen ground its effect on the run-off is greater than otherwise.

Information connecting the fall of rain with the level of underground water is, if anything, even more meagre and is equally unsuitable for general application. The observations available are those

of the depth of water in wells, and in order that these may be accurate, no appreciable draught must be made upon the well. Even if a correct account is kept of the abstracted water, the records do not admit of correction by this means, since it is not possible to tell with certainty the area from which this water is being drawn, and in any case the zone of depression caused by its withdrawal is steadily neutralized by natural processes.

The rapidity with which a well responds to rainfall depends upon its depth, upon the season of year, and upon the nature of the geological strata. Dr. C. P. Hooker [1] has shown that a well sunk in the oolite near Cirencester responded extremely readily to local rainfall showing a wide fluctuation. Mr. R. Cooke and Mr. S. C. Russell,[2] dealing with a well in the chalk near Maidstone, found a sluggish response and a restricted range of water-level. It is probable that sensitiveness is an indication of a small degree of permeability, and that in soil of a highly porous nature the rise and fall of underground water is general rather than local. An important contribution to the literature of the subject, by Mr. D. Halton Thomson,[3] deals with the records of the 84 years 1836 to 1919 at Chilgrove, lying in the high chalk downs of West Sussex. These records, in common with the majority of others, exhibit an almost invariable maximum in the late winter or early spring, a diminution in level till the following autumn, and a rapid recovery during the winter. In years of exceptional rainfall, either in respect of amount or of seasonal distribution, considerable

[1] See *Q.J.R. Met. Soc.*, vol. xxix, p. 263; vol. xxxiii, p. 287.
[2] See *Q.J.R. Met. Soc.*, vol. xxxvii, p. 125.
[3] See *British Rainfall*, 1919, p. 247.

variations from this simple régime occur, amounting on occasion to almost complete inversion.

The accompanying diagram, Fig. 126, gives the the average results for the whole period at Chilgrove. The relation of the well-depth to the actual rainfall is not extremely clear, and a second curve is added showing the estimated effective rainfall computed by deducting from the actual fall an allowance for

Rainfall and Well-Depth at Chilgrove, Sussex.
AVERAGE, 1836-1919.

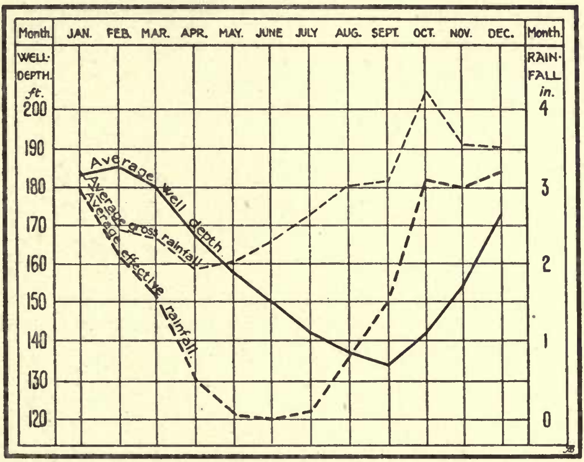


FIG. 126.

evaporation arrived at from the records at Camden Square and Rothamsted. This gives a rough idea of the normal lag of the well behind the rainfall, and illustrates the general relationship of the two phenomena.

The relatively small amount of information which is available on these important branches of hydrometry renders it highly desirable that some means should be found for bringing together in a

collected form the accumulated experience of the large body of engineers in charge of water-works in all parts of the country. A movement in this direction has been made in the recent recommendation of the Water Resources Committee of the Board of Trade,[1] that a hydrometric survey of the British Isles should be commenced forthwith. A task of this magnitude should certainly be undertaken by a Government Department, and should be amplified by the compilation of a complete survey of the distribution of average rainfall. The groundwork of such a rainfall survey has already been prepared by the labours of Mr. G. J. Symons, and a great step towards its realization has been made by the scientific study of the rainfall of the country by Dr. H. R. Mill. Its completion would mark an important advance in our knowledge of the water-resources of the country on both scientific and economic lines.

[1] See Second Interim Report of the Water Resources Committee of the Board of Trade (Cmd. 776, 1920).

GLOSSARY

Adiabatic.—Changes of temperature and density which take place in a substance without interchange of heat from any other body are termed Adiabatic. The word is commonly applied in meteorology to atmospheric temperature changes brought about solely by variations of pressure.

Anticyclone.—An atmospheric pressure system in which the pressure is highest in the centre and decreases towards the periphery. Sometimes referred to as a **High**. In the northern hemisphere the winds in an anticyclone blow in the same direction as the hands of a clock move, around the centre.

Aqueous Vapour.—"Aqueous vapour is always present in the atmosphere, and, although it never represents more than a small fraction of the whole, it has physical properties that give it great importance in meteorology. In a closed space whenever there is a free surface of ice or water, evaporation takes place until the water-vapour exerts a definite pressure of saturation, depending only upon the temperature, and not upon the pressure of the surrounding air. This pressure of saturation is very much greater at high than at low temperatures. . . . Saturated air must at once yield rain or snow if cooled, and even air that does not contain all the aqueous vapour possible will ultimately deposit moisture if sufficiently cooled."—*Meteorological Glossary.*

Average Rainfall.—The total rainfall of a number of periods of equal duration divided by the number of periods.—See **Normal.**

Conservation of Energy.—"The term employed to denote the fact that the total amount of energy in Nature . . . never varies; that energy like matter can neither be created nor destroyed. . . . Energy is always undergoing transformation, visible motion, magnetism, electricity, heat and light being a few of the many forms which it assumes."—H. R. Mill.

Cyclone.—An atmospheric pressure system in which the pressure is lowest in the centre and increases towards the periphery.

Also referred to as a **Depression, Low-pressure-system,** or **Low.** In the northern hemisphere the winds in a cyclone blow in a counter-clockwise direction round the centre. A cyclone is referred to as **deep** or **shallow** according as the barometric gradient (*q.v.*) is steep or slight.

Depression.—See **Cyclone.**

Dew-point.—"The temperature of satur.tion of air, that is to say, the temperature which marks the limit to which air can be cooled without causing condensation."—*Meteorological Glossary.*

Eddy.—A vortical motion set up by obstruction in the path of a moving fluid, such as wind.

Effective Rainfall.—The actual rainfall as observed less an allowance for the portion re-evaporated before the water reaches streams and rivers.

General Rainfall.—The mean rainfall of an indefinite number of points uniformly distributed over an area.

Gradient.—The rate of change of any condition from place to place. Thus the rainfall gradient during any period is the difference between the amounts of rainfall recorded at two places divided by the distance of one place from the other. The word is also conveniently applied to temperature, atmospheric pressure, height above sea-level, and many other variables.—See **Lapse-rate.**

Insolation.—"The solar radiation [*q.v.*] received by terrestrial or planetary objects."—WILLIS MOORE.

Inversion, Temperature.—A condition in which the temperature of the free air increases with height, instead of decreasing as is normally the case.

Ions.—"The component parts into which a chemical molecule is resolved . . . by the electrolytic action of an electric current. Of the two component ions, one is always electro-positive, and the other electro-negative."—*Meteorological Glossary.*

Isobar.—A line on a weather-map passing through places at which the barometric pressure, reduced to sea-level and 32° Fahr., is equal.

Isochronous Line.—A line on a map indicating identity in the time of occurrence of any event.

Isohyet, or **Isohyetal Line.**—A line on a map indicating that the fall of rain is equal at all points through which it passes.

Isomer.—A line on a map indicating an equal proportion. Maps showing the proportion of a year's rainfall which falls in any specific period, such as a month, are termed **Isomeric Rainfall Maps.**

Isopleth.—A line on a map showing equal amounts of any element.

Lapse-rate.—The decrease of temperature per kilometre of height in the free atmosphere. Corresponds to the vertical temperature gradient.

March, Seasonal.—The normal variation of any climatological element through the seasons.

Meniscus.—The curved surface of a liquid in a tube. In the case of water the meniscus is concave and a reading should be made at the lowest point ; in the case of mercury it is convex and a reading should refer to the top.

Millimetre.—1 millimetre = ·04 inch ; 1 inch = 25·4 millimetres.

Normal Rainfall.—The amount of rainfall for any specific place or area, and for any specific epoch, from which the amounts observed over a long period show the smallest mean deviation. A close approximation to the normal rainfall is assumed to be obtained by taking the average value (*q.v.*) of a sufficient number of observations. The smaller the area, and the shorter the epoch, for which the normal value is desired, the longer will the series of observations require to be.

Radiation.—"Radiation is the process by which heat is transferred from one body to another without altering the temperature of the intervening medium. All life upon the earth and all meteorological phenomena are dependent upon the radiant heat and light received from the sun. The earth itself is always radiating into space."—*Meteorological Glossary.*

Rain-field.—The area over which rain is falling at any specified time.

Rain Shadow.—The phenomenon of a relatively small rainfall in a district sheltered by a range of hills from the prevailing rain-bearing winds.

Residual Mass Curve.—A curve constructed by plotting the aggregated departures from uniformity of a series of observations.

Seasonal March.—See **March, Seasonal.**

Splash.—A term used to indicate a more or less isolated area on which rain has fallen.

Thermo-dynamics.—The science concerned with the transformation of heat into other forms of energy and *vice versa,*

Vapour-pressure.—" The pressure exerted by a vapour when it is in a confined space. In meteorology vapour-pressure refers exclusively to the pressure of water-vapour. When several gases or vapours are mixed together in the same space each one exerts the same pressure as it would if the others were not present, and the vapour-pressure is that part of the whole atmospheric pressure which is due to water-vapour."—*Meteorological Glossary.*

Zones, Rainfall.—Areas on a rainfall map bounded by specific isohyetal lines.

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PRINTED IN GREAT BRITAIN FOR THE UNIVERSITY OF LONDON PRESS, LTD.,
BY HAZELL, WATSON AND VINEY, LIMITED,
LONDON AND AYLESBURY.